A GEOGRAPHICAL ANALYSIS OF CHANGE IN A HAWAIIAN SUGARCANE PLANTATION

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ABSTRACT

Efficient use of irrigation water when water supplies are limited is crucial to sugarcane production. This project examines technological change in relation to water management at Hawaiian Commercial and Sugar Company (HC&S) of Puunene, Maui in the context of spatial information management. These include the change from furrow irrigation to drip irrigation, the discontinuation of the evaporation pan network, and managing with a computer water balance model.

A field history database of sugarcane harvests at HC&S provided data for a comparison of furrow irrigation and drip irrigation. A combination of statistical and mapping tools were used to evaluate soil, climate, and management variables over space and time for the entire plantation. The topic of greatest concern to HC&S management is "Where to put water when water is short". An objective of this study was to use a simple geographical information system (GIS) system to spatially organize soil and weather data needed for water allocation decisions.

SCS Soil Survey 7.5 minute quadrangles Wailuku, Maalaea, Paia, Puu o Kali, and Haiku were combined to form a continuous soil map for HC&S plantation. HC&S field boundaries were overlaid with the soil map and a database of soil types by field was created. Forty-five years of harvest information including yield, irrigation, and climate variables for almost 3,000 harvests were analyzed spatially using maps and over time using both maps and graphs. Multivariate analysis techniques were used to analyze relationships between variables with different spatial groups.

Sugarcane yields increased after the plantation converted to drip irrigation. The spatial pattern of yields also changed. With furrow irrigation the highest yields were in the Keahua division which had silty clay loam soils. With drip irrigation, coarser soils in the Maalaea division became the highest yielding. With the discontinuation of the network of evaporation pans in the late 1980s the scale of information collected on water demand was reduced. Water management by computer depends on representative data. Improved weather data will help direct where irrigation water is most needed.

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CHAPTER ONE

INTRODUCTION

Evaluating variability within a large area over long periods of time is necessary for understanding different properties of systems and patterns of variability. With many factors involved, comparisons over time and space may help sort out their relative importance. To understand spatial data it is essential not only to be able to analyze what is going on at different locations at one time but also to see if relationships between locations change with time. This study also involves identifying information needs that may help water management decisions.

The data for this study were provided by Hawaiian Commercial and Sugar Company (HC&S) of Puunene, Maui. The plantation's sugarcane fields cover more than 14,500 ha (35,439 acres) stretching from Paia and Hamakuapoko southward along central Maui to Maalaea Bay. The windward slopes of Haleakala are the watershed for the plantation's surface water supply for irrigation. There are properties of the entire plantation which reflect management as well as a diversity of physical conditions which cannot be evaluated at the field level.

During the last 50 years HC&S plantation has undergone major changes in management, expectations, and in technological options. One recurrent theme throughout this change has been how and where to direct water when water is short. In certain times of the year the water supply from both East Maui Irrigation Co. and deep wells is not sufficient to meet plantation needs. Technological changes that directly relate to water management include: 1) the conversion from furrow irrigation to drip irrigation; 2) replacement of pan evaporation network with a network of automatic weather stations to monitor wind; and 3) using a computer model to manage water.

Methods described in the next chapter involve the examination of interactions in space and time for a large area (an entire plantation) using a combination of mapping and statistical tools. Rather than extrapolate from a small sample, yield data from an entire sugarcane plantation for 45 years is used to view processes of change from the result (yield) looking back at management, soil, and geographical factors in the growth of the sugarcane. The scale of management reflects the scale of data used in making decisions.

Between-field variation can only be studied over a number of fields. Within a particular field there can be variation in soils, plant growth, slope, aspect, and water distribution. The overall significance of factors found to vary within a section or block of a field to the management of the entire plantation depends on how representative, or wide-spread, the phenomenon is.

Understanding spatial data management is important not only for geographical information systems but also for models that require spatial data. The computer model HC&S uses to schedule irrigation is referred to as the Water Balance. Sugarcane in the field needs to have water available to offset transpirational losses and prevent stress. The water balance (HC&S) model is used to schedule irrigation based on estimates of how much water sugarcane needs.

When problems arise with meeting crop water demand with sufficient irrigation water there are several places to look for problems: 1) input data; 2) the model itself; 3) water distrubution; 4) total water available. If input data does not properly represent water demand for the different areas of the plantation, changing the model or water distrubution will not help the situation. Spatial information about the plantation is contained in the input data. Which fields are planted and when determines the pattern of each year's harvest. Simulation models or geographical information systems are similarly dependent on representative data.

Planting dates for sugarcane provide both a spatial and temporal component to data entered in the water balance. The plantation is a mosaic of different fields planted at different times throughout the year and harvested ten months of the year. A two-year crop, sugarcane planting at HC&S is staggered so that about one-half of the fields are harvested each year. The acreage and spatial distribution of the harvest each year must be steady. The amount of water demand is adjusted by age, reflecting leaf area index, and cane ripening. Potential evapotranspiration (PE) is multiplied by a crop coefficient (Kc) adjusting the value to better represent ET for sugarcane specifically. The water balance itself uses a basic bookkeeping method tracking daily soil moisture storage, rainfall, irrigation, deficit, PE, and lost irrigation (runoff + percolation). Irrigation scheduling is managed by 3 irrigation supervisors in each of the four main irrigation divisions Paia, Keahua, Lowrie, and Maalaea.

The change from furrow irrigation to drip irrigation was a major technological change that affected many aspects of sugarcane production at HC&S and caused a change in the spatial pattern of sugarcane production. In the years that followed drip conversion other changes also took place. The savings in water use following drip conversion allowed the plantation to add many new fields. Increased environmental awareness and regulation has led to more careful monitoring of water quality. Concerns by the public about cane burning have been met conscientiously by HC&S management with the establishment of weather stations to monitor wind conditions to minimize the chances of smoke from cane-burning bothering residential areas. This network of automatic weather stations was installed in the late 1980's. The stations can be radio-polled hourly and the data enters a central database. These stations also provide data used to calculate sugarcane water demand for irrigation scheduling, replacing evaporation pans.

By far the most pressing concern at HC&S is "where to put water when water is short". An objective of this research is to examine this in the context of information management. Why does management not have the information to answer this question? Are the data used in water management lacking in spatial or temporal information? Does technological change affect the system? Maps will be used as an adjunct to univariate and multivariate analysis as a way of understanding the spatial implications of different management practices.

Indications were that there might be more efficient and productive use of the water if it were managed to meet the most critical stages of cane growth. The problem is complicated by certain fields located in areas with particularly high irrigation requirements. Soil and solar radiation both relate the geographical location and plant water demand. A strong spatial component seems to be involved in efficient plantation management. In planning this study it was considered that the availability of mapping and GIS tools might be a way to more efficiently handle data spatial relations and in water allocation decisions.

The objectives of this study were:

1. Attempt to spatially organize soil and weather data, using a simple GIS system, to make information in support of water allocation decisions available.

2. Investigate procedures to identify and display effects of spatial and temporal change in an integrated manner.

3. Identify procedures that permit analysis of complex, interrelated data at the district or plantation level such that system interactions can be identified and understood more clearly and in relation to each other.

CHAPTER TWO

MATERIALS AND METHODS

Introduction

Hawaiian Commercial and Sugar Company (HC&S) is located on the island of Maui in the state of Hawaii on the western slopes of Haleakala volcano. The climate of the plantation is strongly influenced by the presence of a high mountain (Haleakala) which blocks the path of the Northeast trade winds creating orographic rainfall on the windward (NE) side and desert conditions on the lee side (Nullet, 1989). HC&S plantation has not taken advantage of the windward rain by moving hundreds of millions of gallons of water per day through a sophisticated ditch system to the fields in the dry leeward areas where it can take maximum advantage of increased solar radiation.

The following section is a brief overview of the methods used in this study. In addition to the materials and methods, a statistical method, canonical variate analysis is presented as an example and a test of the usefulness of the procedure to this study.

Overview of Methods

A simple digital map of the HC&S field boundaries was overlaid on the SCS Soil Survey digital maps for this region of Maui. Soils were then assigned by field according to which soil was dominant. In the cases where fields were made up of multiple soil types, the one that appeared to cover the most area was chosen. In this way soil information was converted from being keyed on map units defined by the SCS soil survey to soils being attributes of the sugarcane fields. Field numbers from the map key were matched with the field numbers in the database key.

Data mapping entails using statistical software to produce relational tables of means, variance or other kinds of spatial data keyed on location such as irrigation division (4 divisions represented by 4 unique data records in the key field) or pan groups (9 groups represented by 9 unique data records in the key field). Maps of spatial groups such as irrigation division are created by selecting all the fields belonging to one division and merging them into one region (dissolving internal boundaries) representing that division. Once the regions listed in the map key and the regions of the data table key match, data can be entered into the mapping software. In addition to being mapped, attributes such as irrigation division, evaporation (pan) group, etc. were identified in the database as classes for spatial analysis.

The data were analyzed both spatially (data maps) and over time (graphs) using univariate statistics for frequency distributions and box plots. Multivariate analysis techniques including canonical correlation analysis and canonical variates analysis (a discriminant analysis similar to principal components) were used to evaluate relationships among spatial groups and among variables within spatial groups. The purpose of this was to test whether spatial groups were different from one another (using the data to discriminate) as a procedure to test whether the pattern seen on the map accurately represent the data. Selection of legend categories affects how mapped variables appear. If groups are found to be different, what factors are most important in making the discrimination.

The conversion from furrow irrigation to drip irrigation had a significant impact on sugar production at HC&S. Harvest data for the two types of irrigation technologies were contrasted and compared both spatially and temporally. Another technological change occurred with the discontinuation of the pan evaporation network in the late 1980s and the advent of automatic weather stations. A comparison is made between the pan evaporation data and the estimated evaporation from the automatic weather stations.

This study was possible only because the plantation invested time and effort into entering comprehensive field histories of all the plantation fields into a digital database. Forty-five years of harvest information including yield, irrigation, and climate variables for almost 3,000 harvests provide the basis for studying spatial relationships through time and the effects of technological change on these relationships. Additional digital map data information on the soils of the plantation was provided by the Soil Conservation Service (now the Natural Resource Conservation Service).

Soil Maps

The Soil Conservation Service (SCS) Soil Survey 7.5 minute quadrangles for Maui contain about 1600 different map unit polygons for the HC&S area. Soil taxonomy was used to aggregate the map units into larger groups making it easier to look for patterns in the soil landscape. Different aspects of soil classification were separated onto individual maps; e.g., soil texture, soil phase, soil series, slope. The plantation field boundaries were matched as closely as possible in latitude and longitude to the SCS Soil Survey digital boundaries. An exact match was not possible because the maps did not have known points in common to use as tie points (points with known x,y coordinates that appear on both maps). Soil information was then identified by field.

SCS Soil Survey Digital Maps: Data Conversion

SCS Soil Survey 7.5 minute quadrangles Wailuku, Maalaea, Paia, Puu o Kali, and Haiku were obtained in digital format from the SCS office in Honolulu. These maps were translated from digital line graph (.dlg) files to polygon format. The quads were combined to form a continuous soil map for the area covered by the HC&S plantation. With digital line graph format, points, lines, and areas are described in arc-node format where an arc is a line segment and nodes the endpoints. The data-mapping software, Atlas GIS for Windows (AGISW), used in this study uses a polygon format rather than arc-node. Instead of being listed as individual line segments, all the line segments belonging to a particular area, in this case a soil map unit, had to be brought together as one polygon and assigned the proper map unit name. Pascal routines were used to create polygons and assign map unit names according to the attribute files which accompanied the .dlg files. Individual map unit polygons belonging to the same soil type were then combined to form a region of that soil type.

The SCS soil maps had been drawn over aerial photographs. In a effort to correct for distortion in the aerial photos, the Maui soil survey quads were rubber-sheeted (adjusted) to fit the 7.5 minute orthophotoquads and then redigitized. Obtaining the refitted quads from SCS before they had been properly edited meant that time had to be spent edgematching the quads and making sure the corners were at the same coordinates as the topographic sheets and orthophotoquads. With AGISW the adjoining boundaries have to exactly match if common boundaries are to be dissolved and the map made continuous instead of being in separate quads. Five quads (Wailuku, Maalaea, Paia, Puu o Kali, and Haiku) were combined together and the quad boundaries dissolved to make a continuous soil map and a complete key of the plantation's soils.

Because AGISW has a limit of 4000 x, y points per region, the map files were generalized (extra points deleted) slightly using an algorithm which helps reduce the number of points with the least loss of information. It was then possible to combine all polygons belonging to one soil series into one region. The purpose of creating regions is to simplify relational data tables needed for data mapping.

Combining Plantation Field Boundaries with the Soil Map

HC&S was already familiar with a soil map provided by the du Pont Company overlaying the SCS soil survey on the plantation map. It became apparent that the area labelled Keahua silty clay loam on the du Pont Company map is actually five different soil map units (probably a map symbol truncation error). The area is made up of Keahua silty clay loam, cobbly silty clay loam, very stony silty clay loam, silty clay, and cobbly silty clay.

HC&S has produced a plantation map which has great detail (roads, housing developments, etc.) for the area outside the fields but at the time this project started the field boundaries had not been drawn in (Fig. 1). A simple map of the plantation fields digitized for an earlier project was used instead. As the map was used for mapping data by field, field boundaries alone were sufficient. The field boundaries had been digitized in latitude and longitude at 1:24,000 and were matched with the SCS soil survey maps. Rubber-sheeting for a more exact fit between the soil map unit boundaries is not possible without tie points.

The plantation map was overlaid on the soil survey map which consisted only of classified soils with areas such as water, quarries, or gullies left blank. The result was a soils map layer (overlay) and a separate map layer with just the field boundaries. Coast lines were added on the field layer for reference (Fig. 2). On this layer all nonfield areas including residential areas are left blank.

Mapping Selected Information from the Soil Survey

The key to the soil map layer, consisting of SCS Soil Survey map legend symbols for the different soil types, was copied to a database program to serve as a key to a data table of attributes that could be used for mapping. Information was entered into the table on soil series, soil texture, soil phase, slope, and soil order. AGISW was used for mapping each of these using the soil map unit as the base map. Figure 3 is an example of mapping soil orders. This map, consisting of

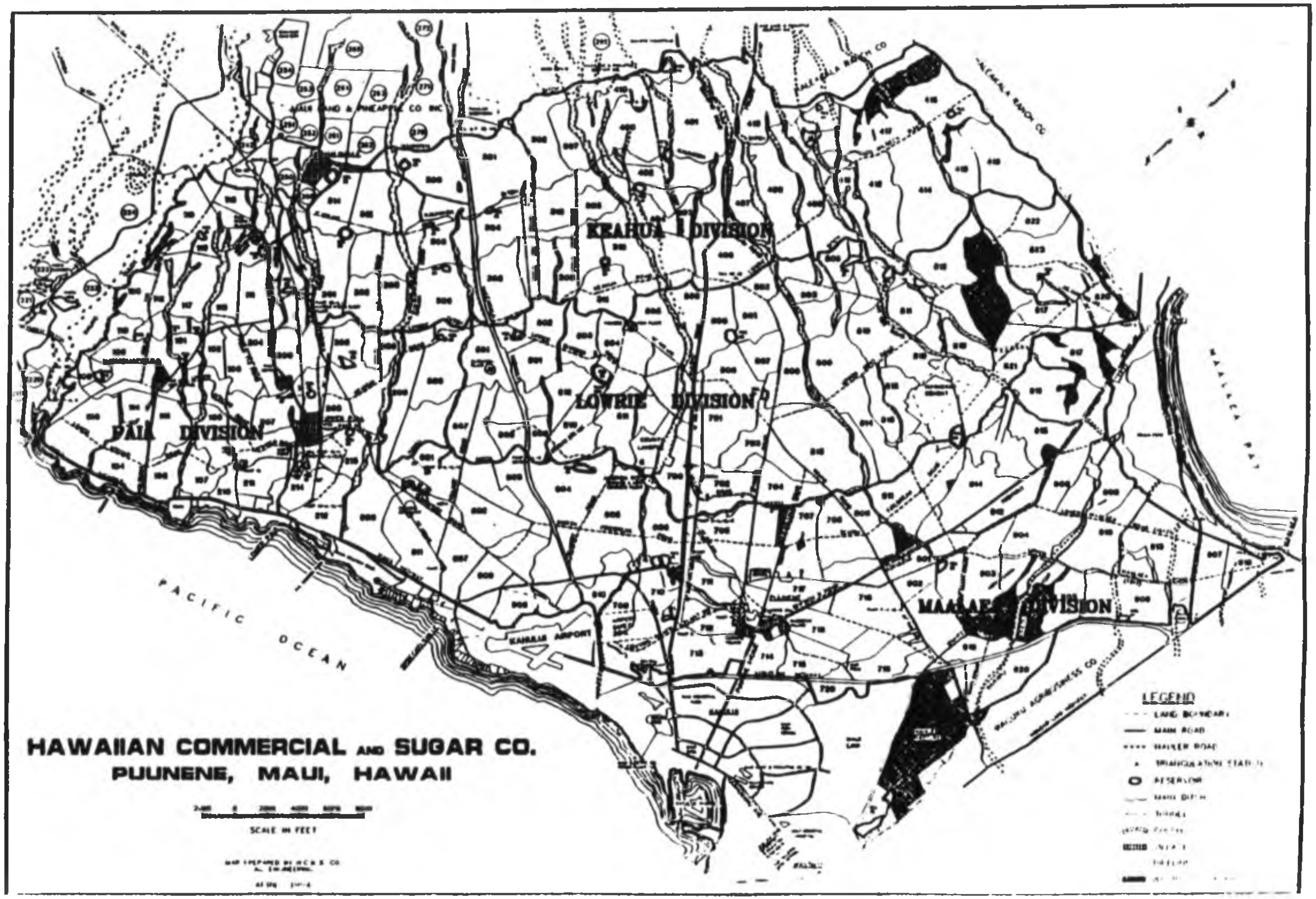


Figure 1. HC&S plantation map showing roads, land boundaries, and subdivisions.

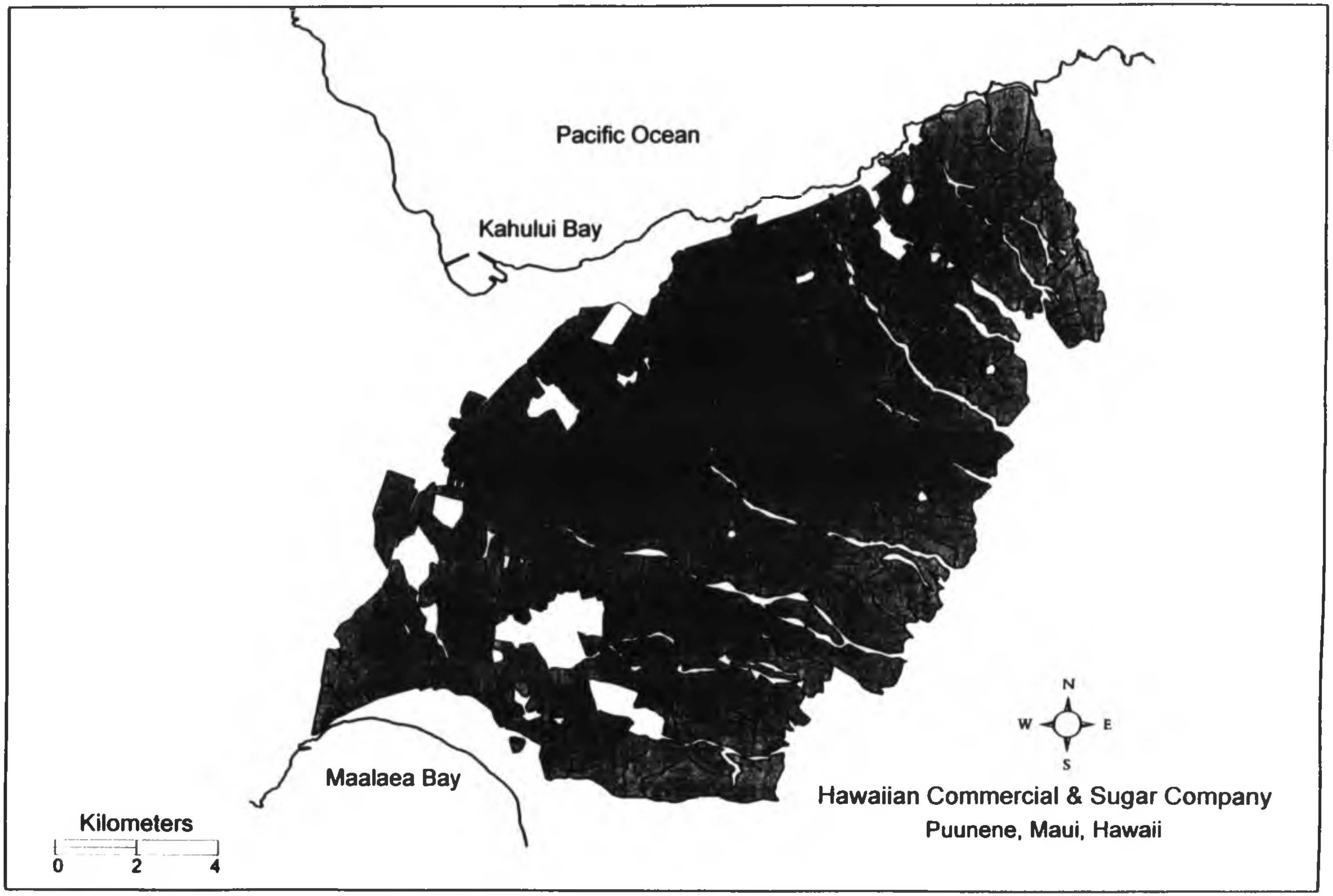


Figure 2. Map layer showing HC&S fields and Maui coastline.

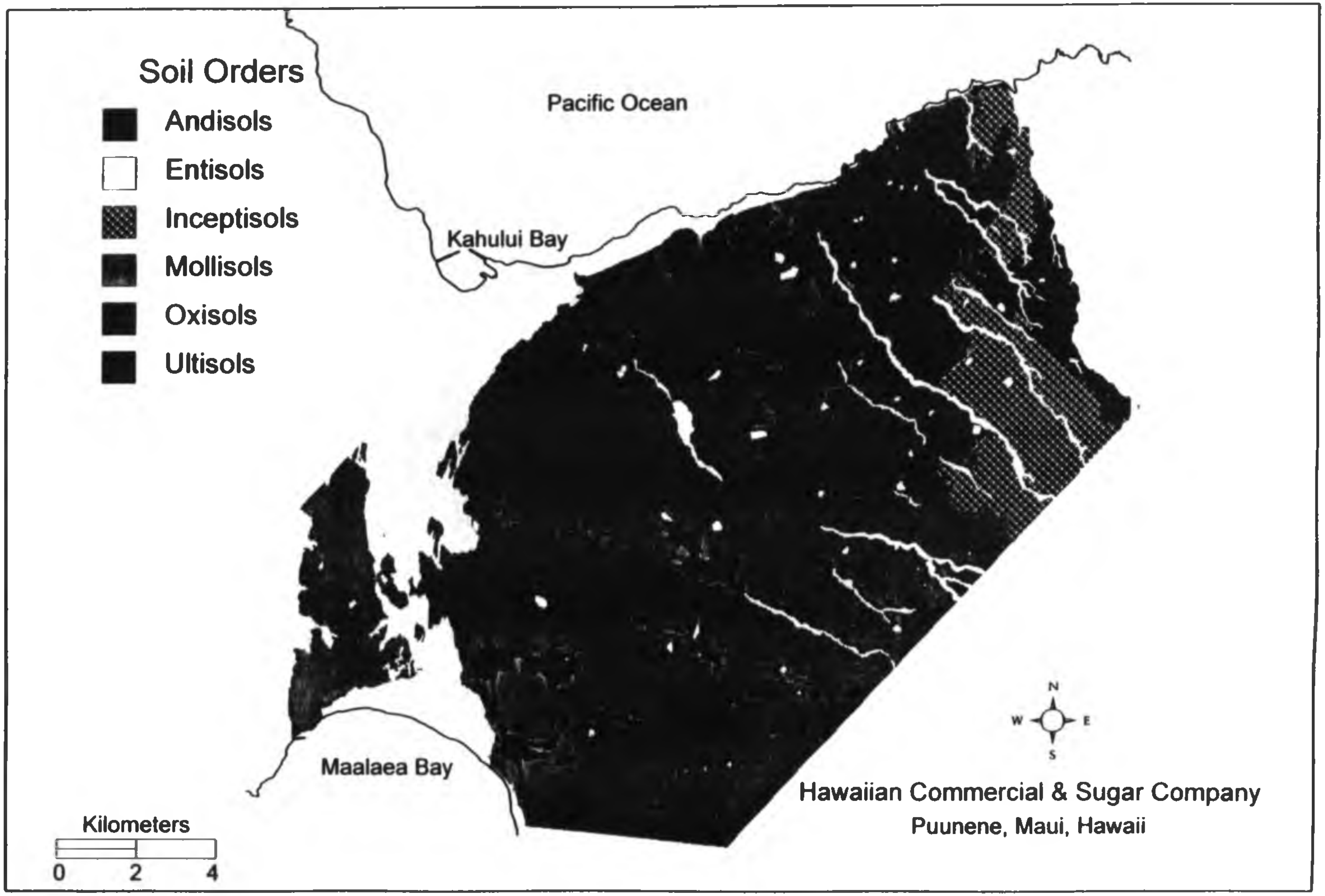


Figure 3. Soil orders map based on the SCS Soil Survey.

information from five 1:24,000 topographic map-size sheets, is extremely condensed as a page-size map. The software allows zooming in to observe individual map units.

Management Data

HC&S has already put considerable effort into developing a spatial database on their computer network. Before the data can be mapped, data management is needed. The key to the database must match the key to the map and the same key used through time. This is a useful way of understanding the spatial and temporal nature of the data. By definition the key must be unique. All duplications will be deleted. The scale at which information is to be displayed affects the choice of key. For example, if the data are all at the field level then the data key can be field numbers. When the data are by blocks within sections of a field, then a much more detailed base map is needed. Obtaining a new base map often consumes unexpected amounts of time.

The most important and most time-consuming part of GIS development is database management. Both errors in the maps and data errors can affect data analysis and display. On the other hand, seeking more precision in the data than necessary can lead to wasted time and money. Data analysis is a necessary part of map development and can help provide insight into management.

Irrigation scheduling is based on data entered into the water balance. The scale of the data entered determines the scale of irrigation management. The field history data used in this analysis includes such variables as age, variety, tons cane acre^{-1}, tons sugar acre^{-1}, brix, pol, purity, potential evapotranspiration, gross water applied, effective water, and water source (ditch).

Harvest Data Characteristics over Time and Space

When researchers design experiments they do so to minimize variation in all factors but those they are studying. When dealing with many variables over a large area such as a watershed or plantation, data has not been controlled by experimental design. Many changes can occur over space and time. In a planned experiment, groups such as blocks and replicates are known and analysis of error can be clearly defined. One purpose of this study was to identify which spatial groups or time periods can be used to sort multiple sources of variation in sugarcane yield in ways that would clarify the relative importance of different factors. Spatial data analysis with large datasets can be used to locate areas for more detailed analysis and to make inferences about relationships between management and the physical environment.

Drip Irrigation Data

The transition to drip irrigation began at HC&S in 1978 at a time when many of the experienced irrigators were retiring. The historical database (1978-1994) contains data on drip irrigation harvests only. Even after the conversion to drip was complete, fields receiving mill waste remained in furrow irrigation. Data variables include the following: field, year, cycle, variety, harvest date, acres, age, total tons cane (TTC), total tons sugar (TTS), gross water applied, effective water, potential evapotranspiration, tons cane per acre (TCA), tons sugar acre^{-1} (TSA), tons cane/tons sugar (TCTS), adequacy, irrigation division, ditch, brix, pol, purity, QR, N, P, K, planting date, month of planting, month of harvest. Fertilizer applications (N, P, K) are recorded in pounds acre^{-1}. Data were averaged over block, section, and variety so that each record represented an entire field. With 158 fields (157 after 405 and 406 were combined), one-half of which are harvested each year, the drip irrigation data include almost 900 harvests. The first data analysis and maps were in English units. The data array was later converted to SI units but the abbreviations for the variables (e.g., TSA) were not changed as they are the variable names in the database.

The plantation has been moving toward no ratooning thus the sugarcane is replanted after each harvest. Entire fields are planted with the same variety at the same time so many of the fields did not have to be averaged over blocks or field sections. Cane is planted 12 months of the year and cane is harvested 10 months of the year. Data recorded by harvest have been totaled over the period beginning with the planting date and ending with harvest. Keeping irrigation and other information directly linked to the growth of the cane and harvest age makes it possible to evaluate yield in relation to other factors.

Gross water applied, irrigation, is calculated using (hours irrigated * flow rate) * efficiency factor. In the water balance used to schedule irrigation, gross water applied over soil moisture storage is not considered effective. Runoff and water that percolates below the root zone do not contribute to soil moisture storage. Effective water is effective rainfall + effective irrigation. Rainfall is counted first up to soil moisture storage (SMS).

In the drip irrigation field history database, effective water (net water applied), a total for the two-year crop cycle, is calculated from rainfall and gross water applied discounting anything over potential evapotranspiration total for the time from planting to harvest. Adequacy (%) = (effective water/potential evaporation) * 100.

Predrip Irrigation Data

The predrip irrigation database contains harvest data for all types of irrigation from 1950-94 and includes rainfall. Furrow records had irrigation recorded as rounds. A round is defined as the amount of water applied by the time the water reaches the lower end of the furrow (Oldeman, 1971).

Other types of irrigation included overhead sprinklers which were experimented with but not adopted. Drip refers to fields whose irrigation values were in inches over the entire crop cycle rather than in rounds. Predrip irrigation data include: field, year, cycle, variety, harvest date, acres, age, rain, irrigation, TTC (total tons cane), TTS (total tons sugar), TCA (tons cane acre^{-1}), TCTS (total tons cane/total tons sugar), TSA (tons sugar acre^{-1}), brix, pol, purity, N, P, and K. If data were recorded by subsections of a field, an average of the sections was substituted so that one record referee to one field. Age and harvest date were used to calculate planting date or ratooning date, month of planting, and month of harvest.

Soil Analysis Data

The soil analysis database is a compilation of data sampled from 1962-92. Soils are tested after harvest. Approximately one-half of the fields are harvested each year and roughly sixty samples are taken. Data include pH, phosphorus (#/AC-FT), potassium (#/AC-FT), electrical conductivity, calcium (after 1980), magnesium (after 1980), and sodium. Sampling methods were changed to being according to soils after 1992. Soil analysis data using the new sampling methods were available for 1994.

Data Tables for the Water Balance Model

There are several tables of data that supply information to the water balance including a listing by irrigation block of irrigation type, acres, ditch, rainfall key station, evaporation (pan) station, irrigation supervisor sequence number and soil moisture storage. The information was consolidated using field number as a key rather than irrigation block. Irrigation division and supervisor sequence number were combined under the heading division supervisor. This table was later enlarged to include soil order, series, texture, and phase. Other tables include data on distance to the mill, record yields of each field, and proximity to residential areas.

Climate Data

HSPAWX software available from the Hawaiian Sugar Planters' Association comes with weather data (solar radiation, rain, temperature, pan evaporation) in a text format that can easily be transferred to another database. At least 30 years of data are included with the program ending about 1991. HC&S provided monthly weather data printouts from 1988 to early 1995 for evaporation, temperature, and rainfall.

Preliminary Data Handling

Raw data from the predrip and drip irrigation field history databases were first plotted against time to look at trends and outliers. Each variable plotted was labeled using the field name. Outlying values that appeared to warrant further investigation were found more quickly with year and field identified on the graph. The drip irrigation fields in the field history database overlapped, with respect to drip irrigation yield variables, with the predrip database. The data seemed to have been entered independently (missing values and data entry errors were in different places) so it was possible to crosscheck the drip information between the two datasets. Data calculations were verified with derived values such as tons sugar $acre^{-1}$ and tons sugar $acre^{-1}$ $month^{-1}$. Missing values were marked and both datasets were uploaded to a mainframe computer for analysis using the SAS statistical analysis system (SAS Institute, Inc,1990).

Frequency analysis with stem and leaf plots, box plots, and tests of normality provided a preliminary analysis of the data. Outliers were only deleted only if they were several standard deviations away from the rest of the field. As outstanding yields are themselves outliers, care was taken not to discount important information. With almost 3000 degrees of freedom, each individual outlying data point has less influence.

Exploratory Statistical Analysis Methods

Soil and climate maps show the physical characteristics of the environment. Inferences can be made from these about how sugarcane is likely to grow. At the plantation level (157 fields distributed over 14,500 ha) it is more difficult to know how yields respond, especially with staggered planting times. Within a planned experiment yield predictions can be made using regression analysis. In discussions with plantation management and personnel at the Hawaiian Sugar Planters' Association it seemed that at the plantation level there was trouble identifying where the best fields were and finding good relationships between irrigation and yield using regression analysis. Yield analyses usually involved looking at the history of one field's harvests over time (every other year).

Plantation management would like to know where to put water when the plantation is short of irrigation water. The information provided for the study does not include water distribution or supply information. No information was given on the use of deep wells to supplement surface irrigation water or how much pump water was distributed to different locations. As result, this evolved into a study of the plantation using field histories as a way to explore past and present relationships between management and environment as revealed by sugarcane yields.

About the time of the conversion to drip irrigation, HC&S expanded its acreage (Fig. 4). Although there are more furrow harvests in the database because there are more years of data available, the acreage of the plantation was less

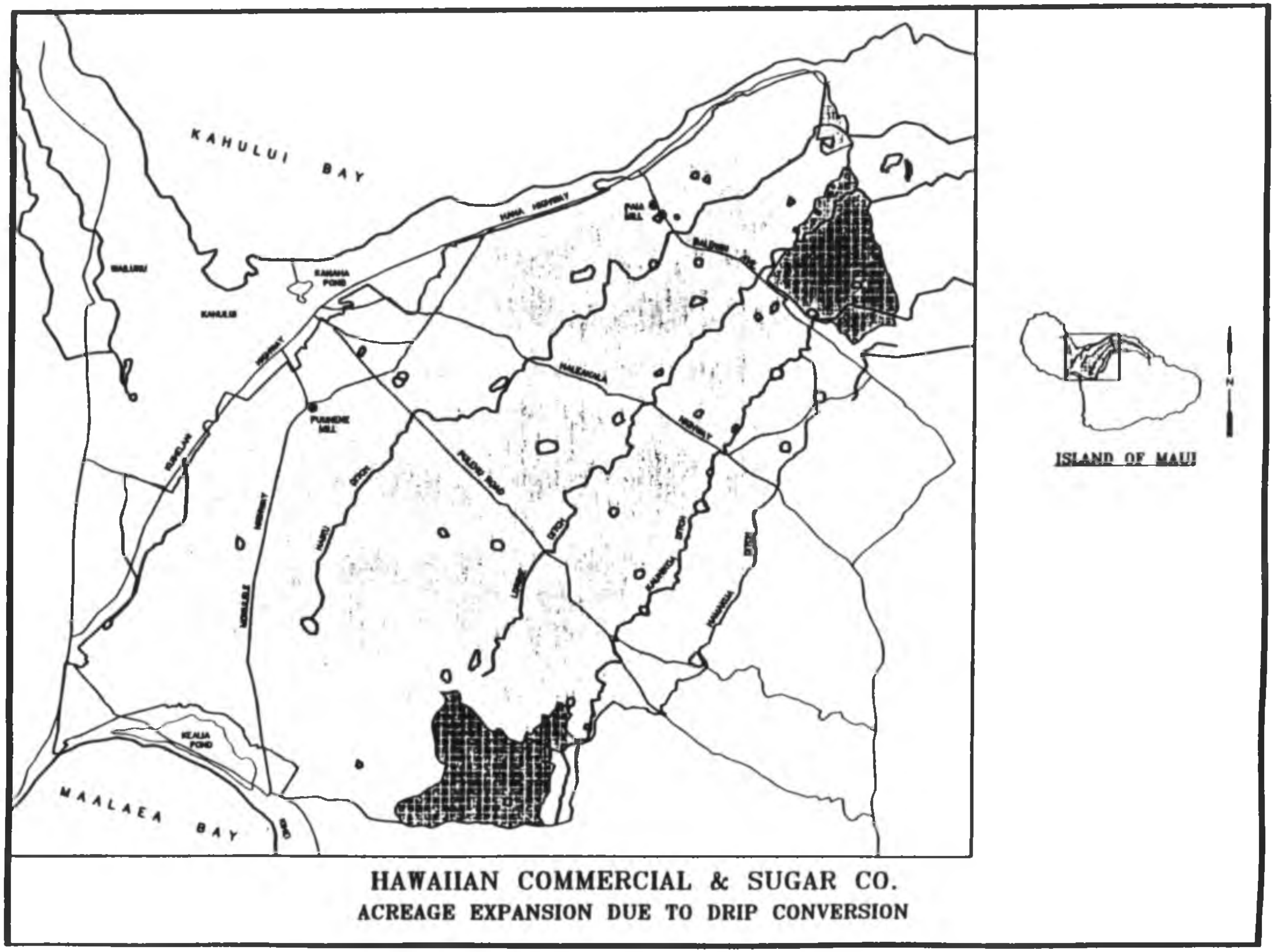


Figure 4. Map of acreage added to HC&S plantation (shaded) after the conversion to drip irrigation.

before the change in irrigation technology. With the 24-month crop cycle it is difficult to hold other factors equal at the plantation scale while examining yield relationships. To test all the possible combinations of factors two at time, as in linear regression, would take too long with more than 3000 data records of more that 20 variables each. Moreover, at the plantation scale information is available in less detail. Canonical correlation, very similar to multiple regression, allows a set of dependent variables to be included in the analysis along with a set of independent variables. For examining causal relationships in large datasets, this is a very useful tool.

Using maps together with canonical variates analysis to identify areas of dissimilarity as well as similarity is another method of exploratory statistical analysis. The object of this research is to look for clues, both spatial and temporal, about the relationship between sugarcane yields, the biophysical environment, and management practices. Identifying groups within which yields have responded similarly will help identify the nature of common factors. Canonical variate analysis is a way of testing how field history variables discriminate between groups including soil order, soil series, soil texture, age, harvest month, and evaporation (pan) group.

Analyzing Between-Field Variability

Fields are the smallest management unit examined in this study. Questions investigated involve between-field variation only, both spatially and over time. Field history data, linked to the two-year crop cycle, enlarges the view of time to focus on the plantation as a mosaic of sugarcane populations at different ages. Which fields have the highest yields? Which have the lowest yields? Are years different? Does it matter when sugarcane is planted or harvested? Do sugar yields increase with crop age? What were the effects of drip conversion at the plantation level? Can management affect yield variability?

Spatial Attributes

An important part of this analysis involves the comparison of groups in time or in space. This is similar to an ecological analysis in that relationships between the plantation (community), sugarcane (plants) and the environment are investigated. These groups were not only used for mapping, but also for univariate and multivariate analysis. In terms of sugarcane management, groups defined by the key to water balance input and output provide a way to view what the water balance "sees".

Analyzing Variables Simultaneously

Both data mapping and multivariate analysis are different from univariate analysis in that relationships between variables are analyzed simultaneously, rather than analyzing one variable at a time (Dillon and Goldstein, 1984). Data can also be analyzed for different time periods as well as locations. Maps and three-dimensional surfaces can be used to display variables from different locations simultaneously. To understand spatial data it is essential not only to be able to analyze what is going on at different locations at one time but also to see if relationships between locations change with time. It is important to remember that discussing a variable such as tonnes sugar hectare^{-1} (TSA converted to Mg ha^{-1}) at the plantation means tonnes sugar hectare^{-1} for all fields in the group or time period referred to.

In statistics, data units can be changed by multiplying by a constant; e.g., acres * 0.405 = hectares without changing variability. If harvest ages for all the fields harvested in 1995 were the same, age can be thought of as a map overlay with 60 fields all represented by a constant. If the harvest age is 24 months for all fields, dividing tonnes sugar hectare^{-1} by age will produce a new map of tonnes sugar hectare^{-1} month^{-1} having exactly the same pattern of between-field variation as tonnes sugar hectare^{-1} even though it is a different variable. Similarly, in multivariate analysis, tonnes sugar hectare^{-1} and tonnes sugar hectare^{-1} month^{-1} will only be as different as the harvest ages for the different fields are. If yield has one spatial pattern and age has another, a new spatial pattern will appear for yield divided by age.

Duncan's multiple range test

Duncan's multiple range test is a univariate method of ranking means one variable at a time. This method was used to summarize relationships between means for one variable in different groups and to see if results were similar to those from canonical variates analysis. Using more than one method to examine the same set of data is a way of cross-checking the stability of results.

Multivariate Analysis

Canonical analysis arose partly to facilitate the joint analysis of two sets of variables (Gittins, 1985). Canonical correlation using a set of yield variables with a set of irrigation variables, was investigated as a method of evaluating cause and effect. Redundancy analysis in canonical correlation tests of how much of the variance in yield is explained by the irrigation variables. Variables such as potential evapotranspiration, gross water applied, and rainfall are accumulated over the crop cycle and thus have a high correlation with age.

Canonical variate analysis is different from canonical correlation in that variables are not separated as independent or dependent and one set of variables may be structured as classes (species, soil type, etc.). According to Digby and Kempton (1987), "The purpose of the analysis is to produce an ordination of the units in a small number of dimensions which emphasizes the major patterns of variation in their responses." To practice this method, a set of field history variables was tested to see how well they discriminated between the 4 main irrigation divisions (the class variable).

To test canonical variates analysis as a method for use in this study, an example was chosen using tonnes sugar hectare^{-1} (TSA), potential evapotranspiration (PE), gross water applied (GW_APPL) and elevation (ELEV) as one set of variables and the four HC&S irrigation divisions: Keahua, Lowrie, Maalaea, and Paia as the other. The drip irrigation database (1978 to 1994) has

881 observations, referred to as harvests (Table 1). Observations with missing values are deleted.

Multivariate analysis involves data reduction techniques for large datasets. The principle of canonical variates analysis is to explain as much of the total variance as possible with as few canonical variates as possible. Each canonical variate (CAN) is a weighted linear combination of the variables. The largest amount of variability is accounted for by the first canonical variate (CAN1). The next canonical variate (CAN2), uncorrelated with the first, accounts for less of the variation. A test of significance each canonical variate is useful in deciding how many variates to retain (Dillon and Goldstein, 1984)

Table 1. Class level information for canonical variates analysis using 4 variables (drip) and 4 classes (irrigation divisions) for a total of 881 observations (877 df within classes and 3 df between classes).

Division	DIV	Harvests	Proportion
Keahua	K	262	0.297
Lowrie	L	277	0.314
Maalaea	M	104	0.119
Paia	P	238	0.270

Are irrigation divisions different? Measures of similarity, or dissimilarity, between groups are used in multivariate analysis. Mahalanobis distance is recommended for variables with very different scales of measurement (Digby and Kempton, 1987). The SAS analysis package (SAS Institute Inc, 1990) computes the Mahalanobis distance based on the squared distances between irrigation division means.

In Table 2, the highly significant probabilities for distances between Keahua and Lowrie, Keahua and Maalaea, Lowrie and Maalaea, Lowrie and Paia, and Maalaea and Paia indicate that these distances are greater than the similarity measure indicating the irrigation divisions are different. Lack of significance between a pair of irrigation divisions would indicate a lack of difference.

Table 2. Probability greater than Mahalanobis distance for squared distance to irrigation divisions (DIV) at the 0.05% level.

From DIV	K	L	M	P
K	1.0000	0.0001	0.0001	0.0001
L	0.0001	1.0000	0.0001	0.0001
M	0.0001	0.0001	1.0000	0.0001
P	0.0001	0.0001	0.0001	1.0000

In canonical analysis, vectors called eigenvectors are projected into multidimensional space to maximize the distance between groups (Digby and Kempton 1987). The eigenvalue is the root. In Table 3, 79.91% of the variance is accounted for by the first canonical variate (CAN1) and 19.98% by the second (CAN2). The third canonical variate (CAN3) is not significant at the 0.05% probability level; the null hypothesis that the canonical coefficients = 0 is not rejected.

Table 3. Eigenvalues, accounted-for variance (%) and F tests				
CAN	Eigenvalue	Variance (%)	F	Pr > F
1	1.720	79.91	129.60	0.0001
2	0.430	19.98	57.53	0.0001
3	0.002	0.11	1.0178	0.361

Which variables account for most of the difference between divisions? In the following table, the variable with the greatest weight (loading), 0.9833 on the first canonical variate (71.91% of the variance) is elevation. Potential evapotranspiration, gross water applied, and tonnes sugar hectare^{-1} dominate CAN2, 19.98% of the variation.

Table 4. Total canonical structure.			
	correlations (loadings)		
Variable	CAN1	CAN2	CAN3
TSA	0.0747	0.9958	0.0533
PE	0.5312	0.8347	0.1453
GW_APPL	0.2532	0.9672	0.1590
ELEV	0.9833	-1.1817	0.0023
TSA = tonnes sugar hectare^{-1} , PE = potential evapotranspiration, GW_APPL = gross water applied, ELEV = elevation			

Figure 5 shows the separation of the four irrigations divisions when plotted on the first two canonical variates axes. The differences between irrigation divisions are primarily due to elevation along the x axis (CAN1). The symbols for

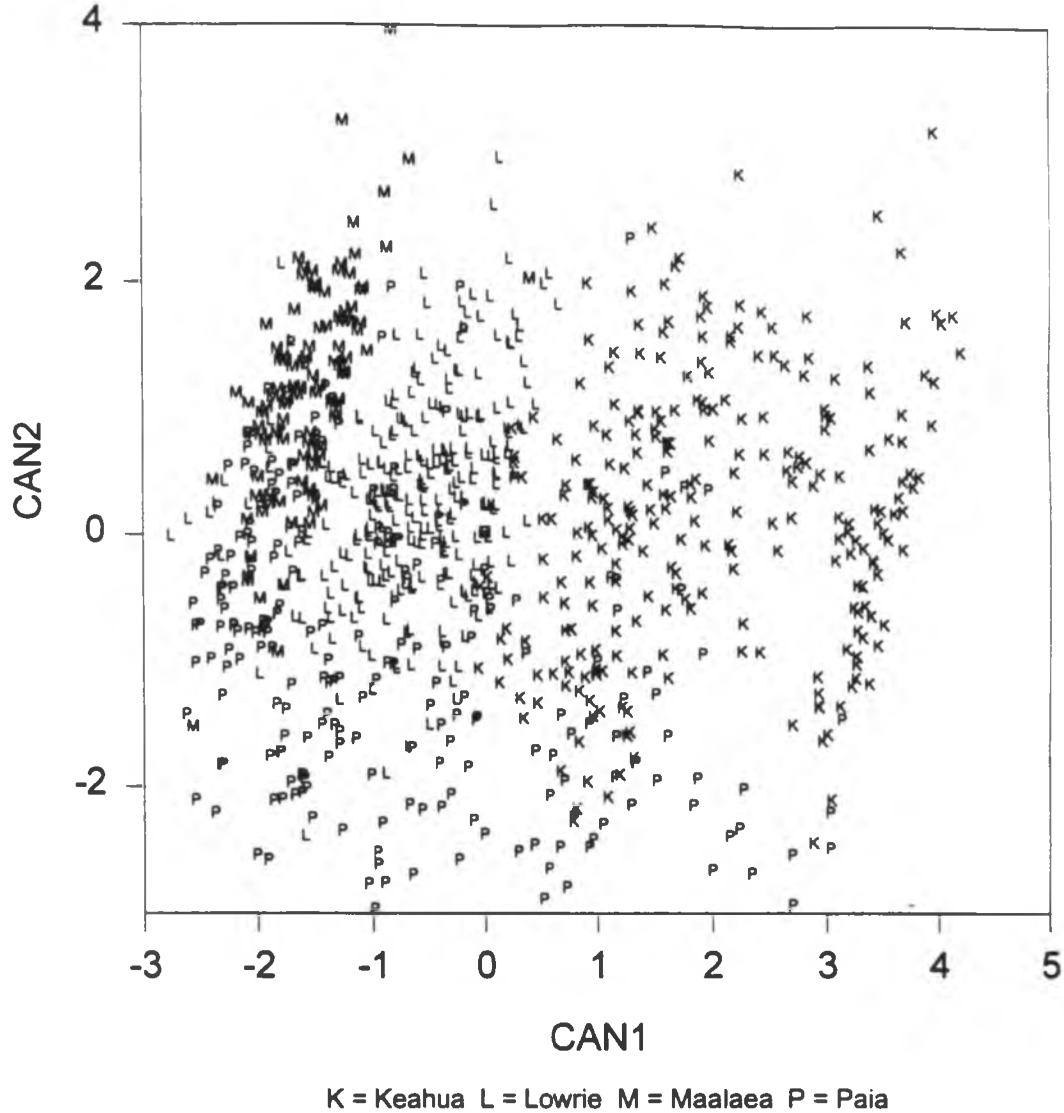


Figure 5. The first canonical variates axis, CAN1, accounts for 79.91% of the variance. The second canonical variates axis, CAN2, accounts for 19.98% of the variance. Symbols indicate irrigation divisions.

Paia Division are near each of the other three divisions along the y axis (CAN2), reflecting some overlap in tonnes sugar acre^{-1}, potential evapotranspiration, and gross water applied. Keahua and Maalaea are farthest apart. These results are consistent with the map of irrigation divisions (Fig. 6). Paia Division borders each of the other divisions, Keahua (upper elevation) is farthest from Maalaea Division (lower elevation).

Map Analysis Methods

HC&S Co. publishes a Cane Crop book each year, which contains individual fields maps, originally drawn from aerial photographs, showing field sections and irrigation blocks. To make a detailed plantation map combining all fields would involve much more cartographic work than is possible in this project. Making matters more complicated, the harvest blocks, areas planted at one time with one variety, did not necessarily match the irrigation blocks. If an irrigation block was planted with cane of two different ages, the lack of match between harvest block and irrigation block could be a problem if the water needs of the sugarcane are different. In the interest of keeping the map key manageable, field means for the 157 fields were used for data analysis and mapped by field.

The first maps made were oriented to match the plantation map (Fig. 1) with Kahului at the lower side of the map with the view from the ocean looking toward Haleakala. The first soil maps of soil series, order, texture, and phase were also made this way. The data was first mapped using English units for easier comparison with other studies of sugarcane production. A new plantation map,

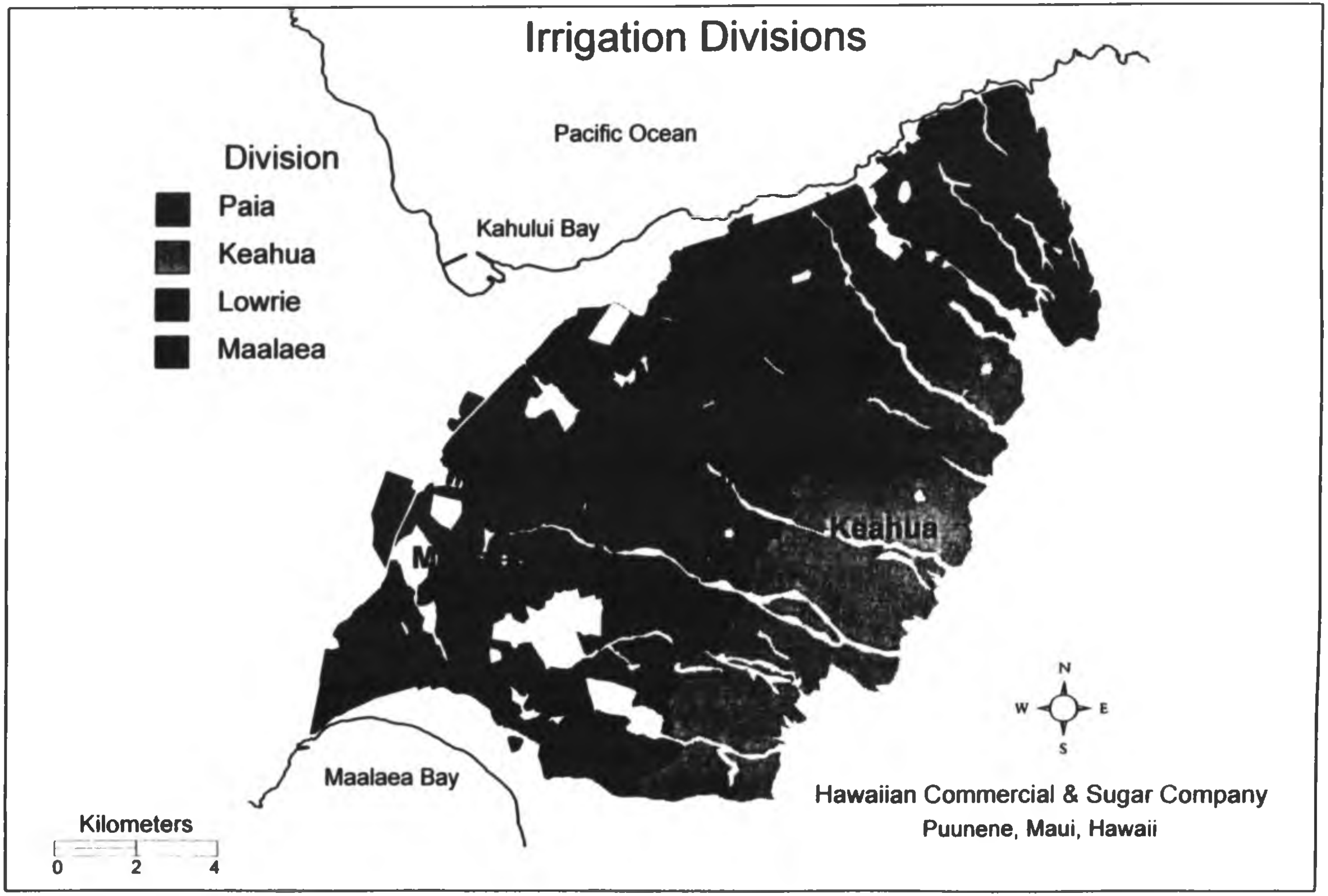


Figure 6. Map of irrigation divisions at HC&S.

oriented with north toward the top of the page, was later developed and the data units were converted to SI units.

The field history and predrip irrigation databases were uploaded to SAS on a mainframe computer. Tonnes sugar hectare^{-1} and tonnes cane hectare^{-1} were found to be normally distributed and did not require transformation. The variables adequacy, brix, pol, and purity had highly skewed frequency distributions. As suitable transformations were not found, these variables were used only in an exploratory fashion and not for tests of significance (Gittins, 1985). Maps were used to display means and standard deviations calculated using SAS.

Data Mapping as a Visualization Tool

Sugarcane is harvested every other year at HC&S so that only one-half the fields are harvested each year. Two year's harvest data for each variable were mapped together to make a more complete map. Even with two harvests/map, many maps were required to display all possible variables for harvest years since 1950. The intent was to use data maps to visualize spatial changes over time.

Coordinating Statistics, Maps, and graphs

Maps of the same groups or classes used in the multivariate analysis could be used for interpreting the results. For example, maps of variables by irrigation division were used to evaluate the results of the test of canonical variates analysis described above. Codes representing different spatial or temporal classes were used as data labels in plots of data over time as another way of looking for patterns.

CHAPTER THREE

RESULTS

Introduction

Material generously provided by HC&S Co. has made it possible to analyze relationships between the plantation, the sugarcane crop, and the environment over space and time. Before the conversion from furrow to drip irrigation, experiments were conducted on drip irrigation efficiency. Enough years have passed and fields harvested since HC&S converted to drip irrigation that a comparison is possible between drip irrigation and furrow irrigation providing a spatial view of technological change.

This section summarizes the results of a spatial data analysis. The methods of analysis, described in the preceding Materials and Methods section, involve a mixture of statistical, graphical, and spatial analyses in an attempt to view variability from enough different angles that light could be shed on relationships involved. The maps included in this chapter are intended as a data visualization method to evaluate changes in temporal or spatial patterns. Discussion of the results will largely be postponed until the following chapter.

Graphing Change over Time

Data from the predrip irrigation database, including all irrigation types, were plotted against time for harvest years 1950-1994 before the data were edited or averaged by field. Three graphs (Figs. 7-10) are examples of raw data in this database. Figure 7 is a graph of tonnes sugar hectare^{-1} over more than forty years.

The change from furrow to drip irrigation is noticeable not only by the increase in yield beginning in the late 1970s and early 1980s but also the increase in variability. Fields converted to drip irrigation had higher yields while fields used for mill waste remained furrow irrigated and low yielding. This disparity between mill fields and the most productive fields is reflected in the variability.

Rainfall, recorded by harvest year, is cumulative rainfall for each field or section of a field for one cane crop. In Fig. 8, the increase in rainfall in the last 20 years reflects that the data is by crop. The apparent increase in rainfall reflects the addition of fields in the Hamakuapoko region during drip expansion. These fields have the highest rainfall. The range of rainfall is attributable to spatial variation. The most windward fields have the highest rainfall and the lowest rainfall values are for the driest, most leeward areas of the plantation. Complicating the pattern is the effect of age. The older the cane is harvested, the more time over which rainfall can accrue.

Data accumulated over the entire age of the crop is necessarily highly correlated with age. The usual age at harvest is 24 months. If fields are carried over from the previous year the harvest age will be greater. Figure 9 shows the age in months of sugarcane harvested from 1950-1994. From the late 1960s to the late 1970s the range of age seems quite uniform. Sugarcane harvested in 1991 was relatively young.

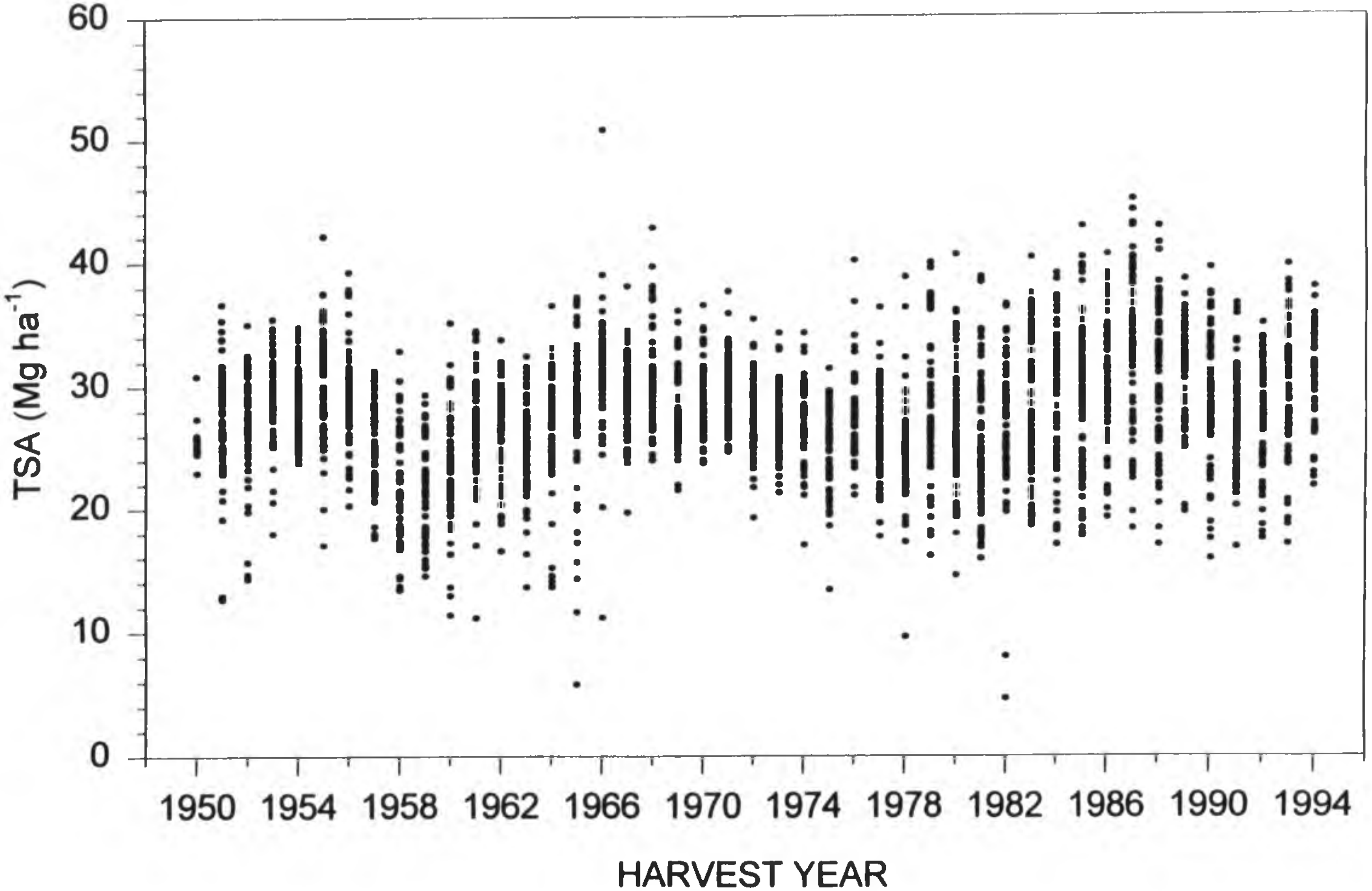


Figure 7. Tonnes sugar per hectare (TSA converted to Mg ha^{-1}) for fields harvested between 1950 and 1994. Each symbol represents one field's sugar harvest.

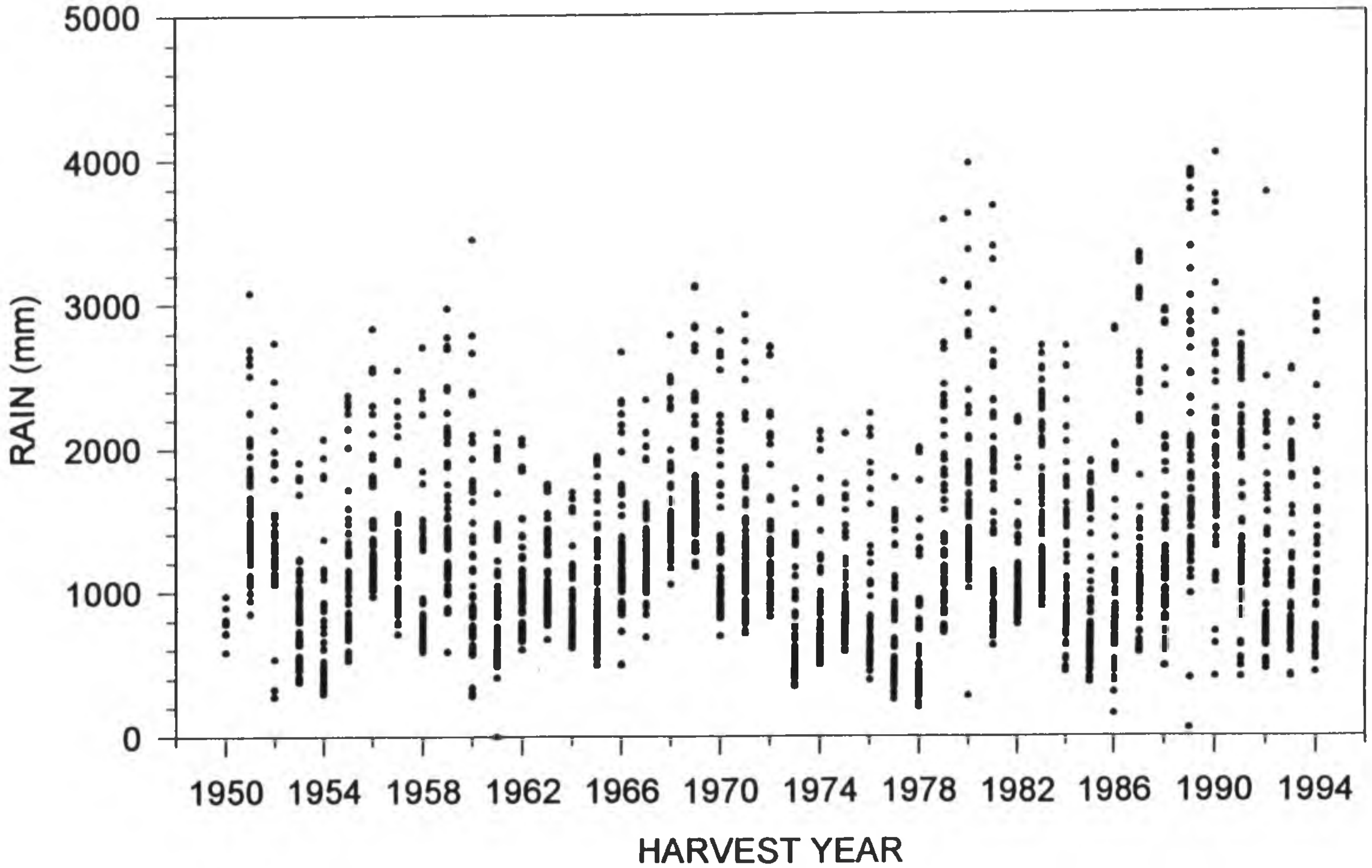


Figure 8. Rainfall total (mm) for each harvest. Each symbol represents the accumulated rain for the harvest from one field.

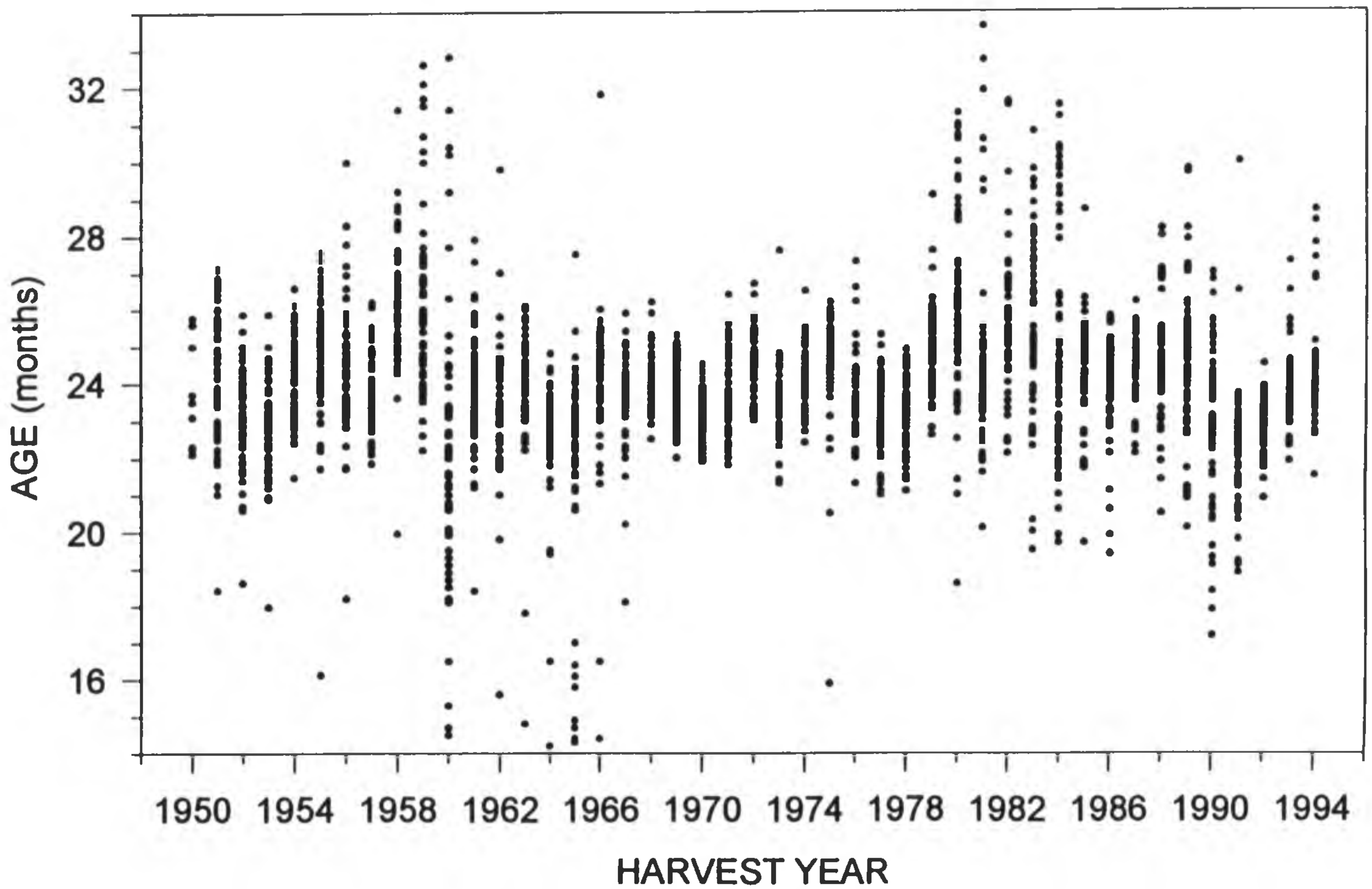


Figure 9. Age at harvest (months) by field for harvest years 1950-1994.

Soils

Soil Maps

As described in the previous chapter, SCS soil survey 7.5 minute (1:24,000) quads were combined into one SCS soil map for HC&S. The base unit for the soil maps is the soil survey map unit. As there are hundreds of separate polygons, the maps do not make satisfactory viewing unless specific areas are zoomed in on using the AGISW software. The soil series map (Fig. 10) should be printed in color on a much larger page. Otherwise, there are too many soil series in the legend to distinguish easily.

Jaucus and Puuone sands come across the saddle of Maui (Fig. 10). Pulehu soil series is adjacent to the sand. Paia, Haliimaile, and Hamakuapoko soil series are located in the northeastern (more windward) section of the plantation. The long white areas on the map indicate gulches, and the smaller white areas are reservoirs or quarries. Soil series covering the most fields include Paia, Keahua, Waiakoa, and Molokai. As indicated in Fig. 3, most of the plantation's soils belong to the soil order Mollisols. Soil series Ewa, Keahua, Paia, Pulehu, and Waiakoa are all Mollisols.

Soil texture (Fig. 11) is an important consideration in determining how much water can be stored by the soil. Most of HC&S plantation is classified as silty clay loam. Silty clay is located in the higher rainfall areas. The sands were windblown across the saddle of Maui from Kahului to Maalaea Bay. Two other maps, soil slope and soil phase, are not shown. Together the four maps display

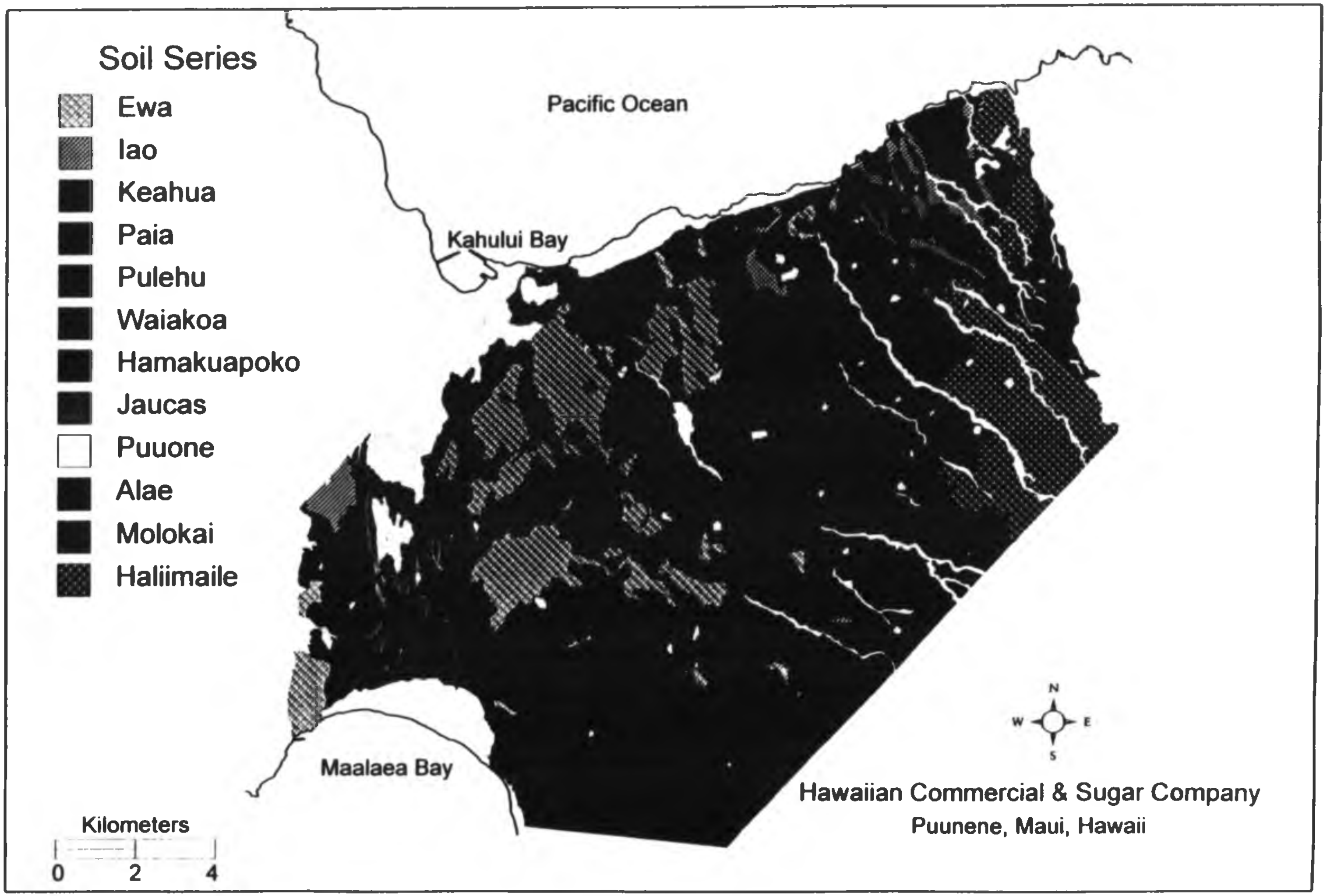


Figure 10. Soil series map of HC&S plantation based on the SCS Soil Survey.

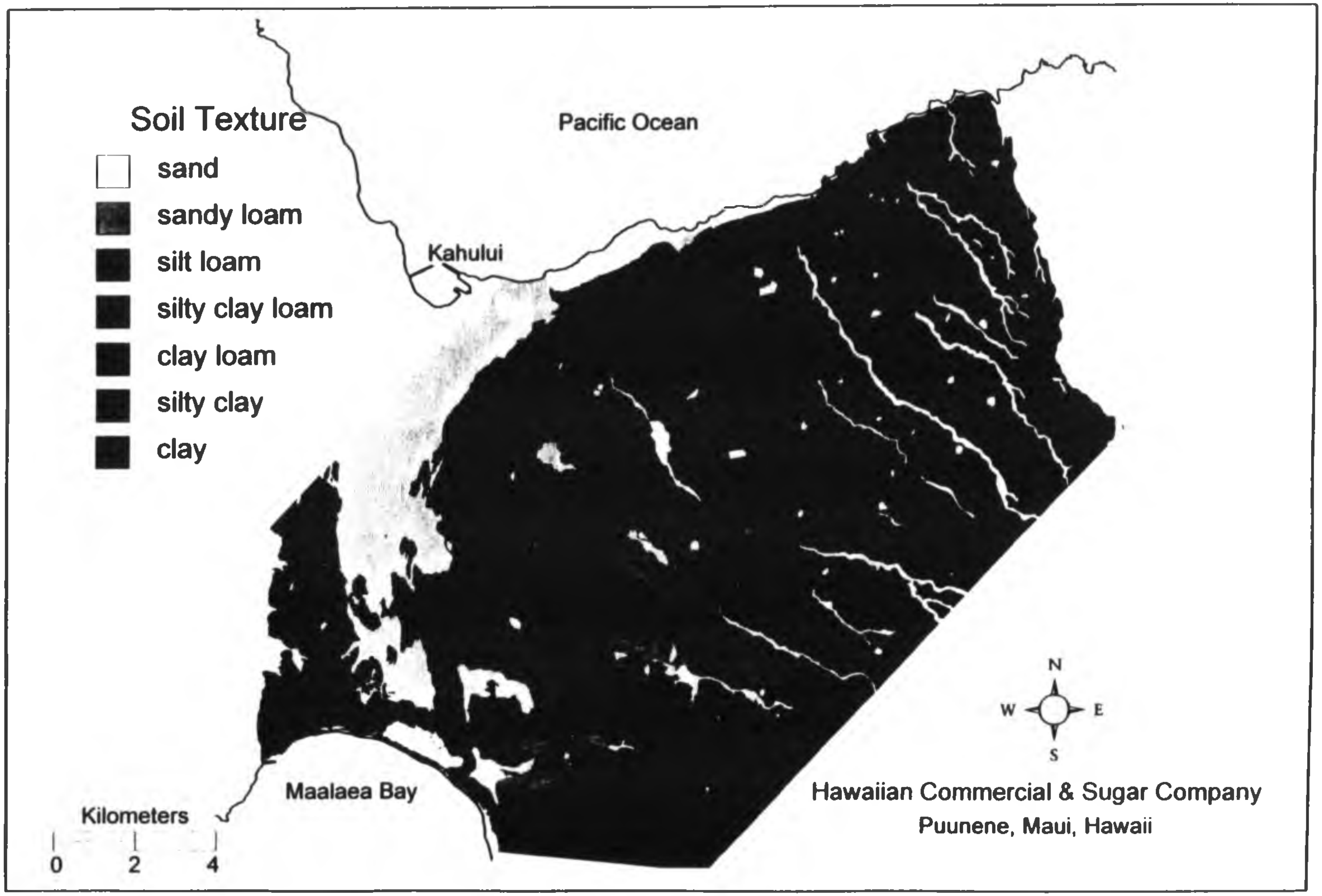


Figure 11. Soil texture map of HC&S plantation based on the SCS Soil Survey

the characteristics of each soil type. For example, soil map unit WgB in the map unit key represents soil type "Waiakoa very stony silty clay loam 3 - 7% slopes". This information is included in four overlays: 1) soil series (Waiakoa), 2) soil texture (silty clay loam), 3) soil phase (very stony), and 4) soil slope (3% - 7%).

The purpose of these soil maps is not for printed output, but rather to use as an overlay on the HC&S fields so that soils could be keyed on fields, making it possible to use soils as class variables in statistical analysis. Additional maps with detail on different soils will be provided in another section..

The soil moisture storage values (Fig. 12) were originally developed to represent the amount of water stored in the soil at an average rooting depth for furrow irrigation obtained from soil moisture retention curves. It was demonstrated at the plantation that these values have been adjusted many times in an effort to adjust the water balance. Without a record of what the original soil moisture storage values were and what changes have been made, it is difficult to evaluate these values. The highest soil moisture storage values have been assigned to the Keahua Division with low values assigned to the silty clays in Paia Division.

Soil Analysis Data

Soil analysis data for 1994 were mapped by field. Spatial patterns of pH, potassium, calcium, sodium, electrical conductivity, and magnesium (not shown) seemed to follow an inverse pattern to rainfall with the highest values where there is the least rainfall. Phosphorus did not follow this pattern. Unfortunately, the

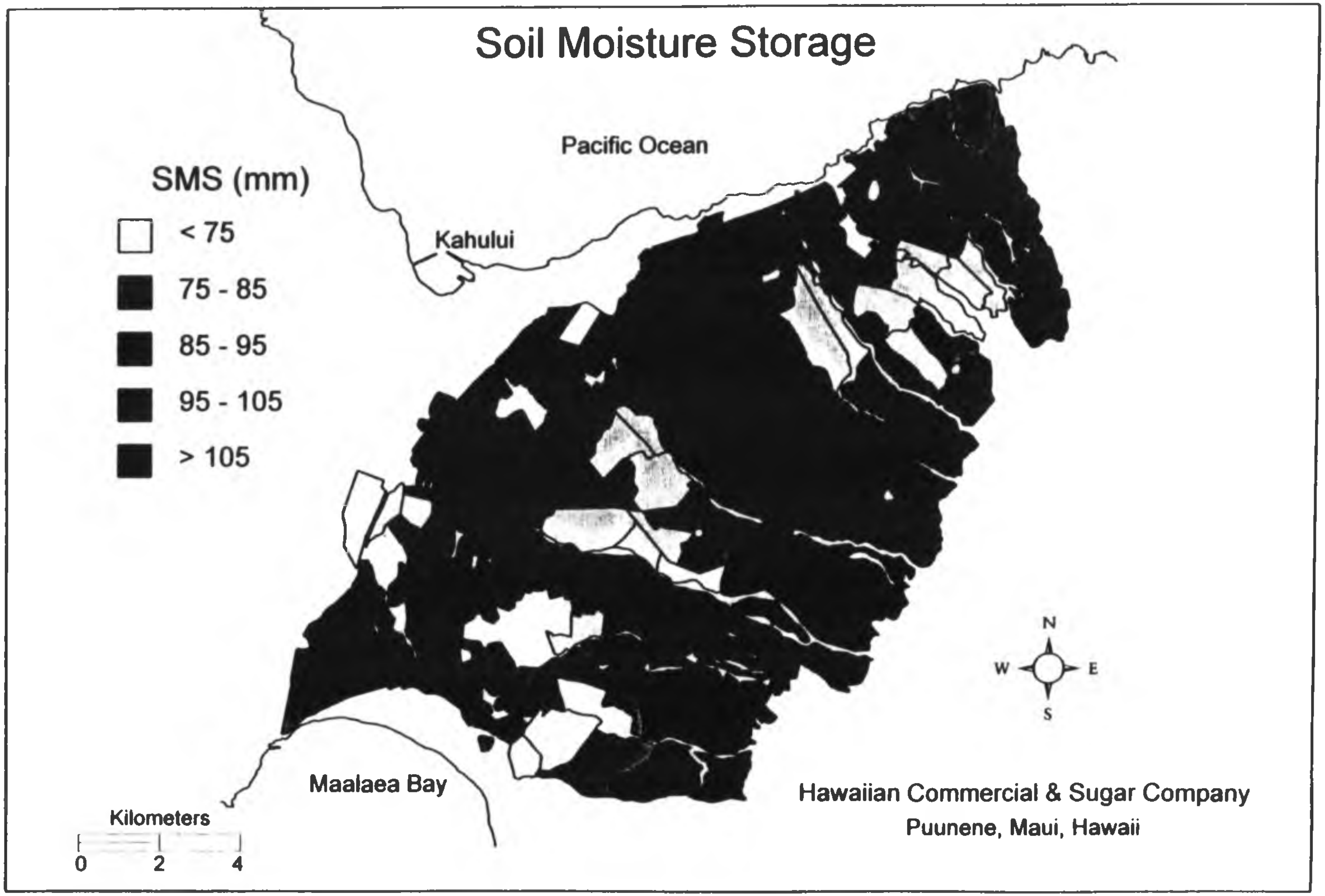


Figure 12. Soil moisture storage (mm) map.

soil analysis data from 1962-92 and 1994 did not include sufficient information on units or extraction methods. Variability is all that can be examined without knowing units of measurement.

Soil test results for pH by year (1962-1992) are plotted on Figs. 13 and 14. A surprise result of plotting these values is the similarity of variability from year to year when fields are harvested every other year. Even though the same individual fields are not harvested each year, the spatial distribution of pH as indicated by the range of values appears constant from year-to-year. This may be partly determined by the need to balance the distance cane is hauled to the two mills, Paia and Puunene. Using field numbers as data labels, the range of pH values can be shown to go from the highest rainfall areas (low pH) to the highest evaporation areas (high pH).

Figures 15 and 16 show soil analysis results for potassium by year (1962-1994). The data were not averaged by field and not edited. Zero values may be missing values. With so much data, points overlap and it is difficult to judge where the means are. Potassium applied as fertilizer (kg/ha) by harvest year 1950-94 is shown on Fig. 17. From about 1966-1975 potassium was applied at many different levels up to 500 kg/ha. In the late 1980s, the amounts of fertilizer applied were reduced. Without knowing the composition of the fertilizer material, the increased fertilizer efficiency with drip irrigation, or any other information, Fig. 17 cannot be fully interpreted..

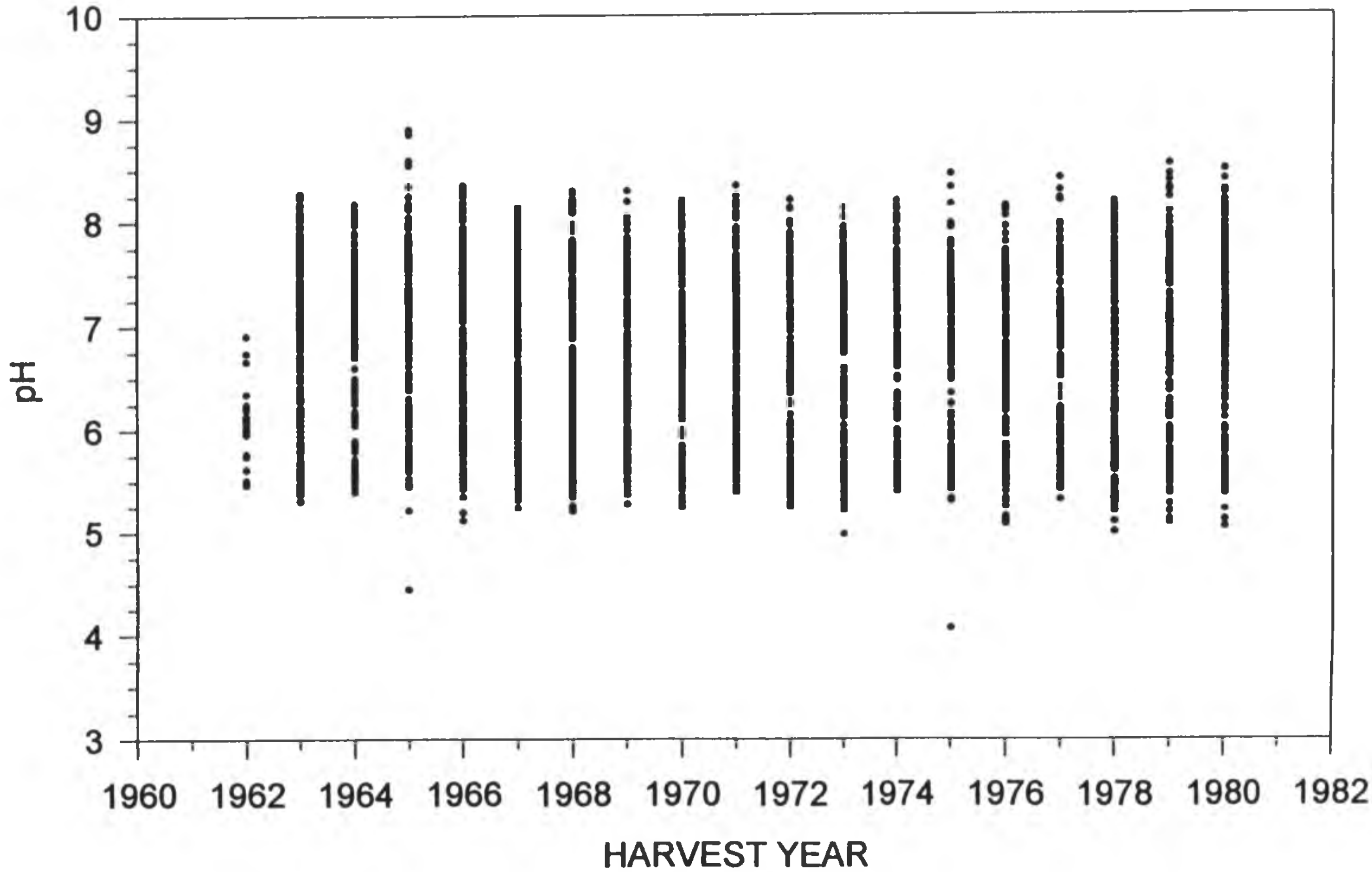


Figure 13. Soil pH data by field from 1962-1980. Soil analysis data is collected after the cane is harvested.

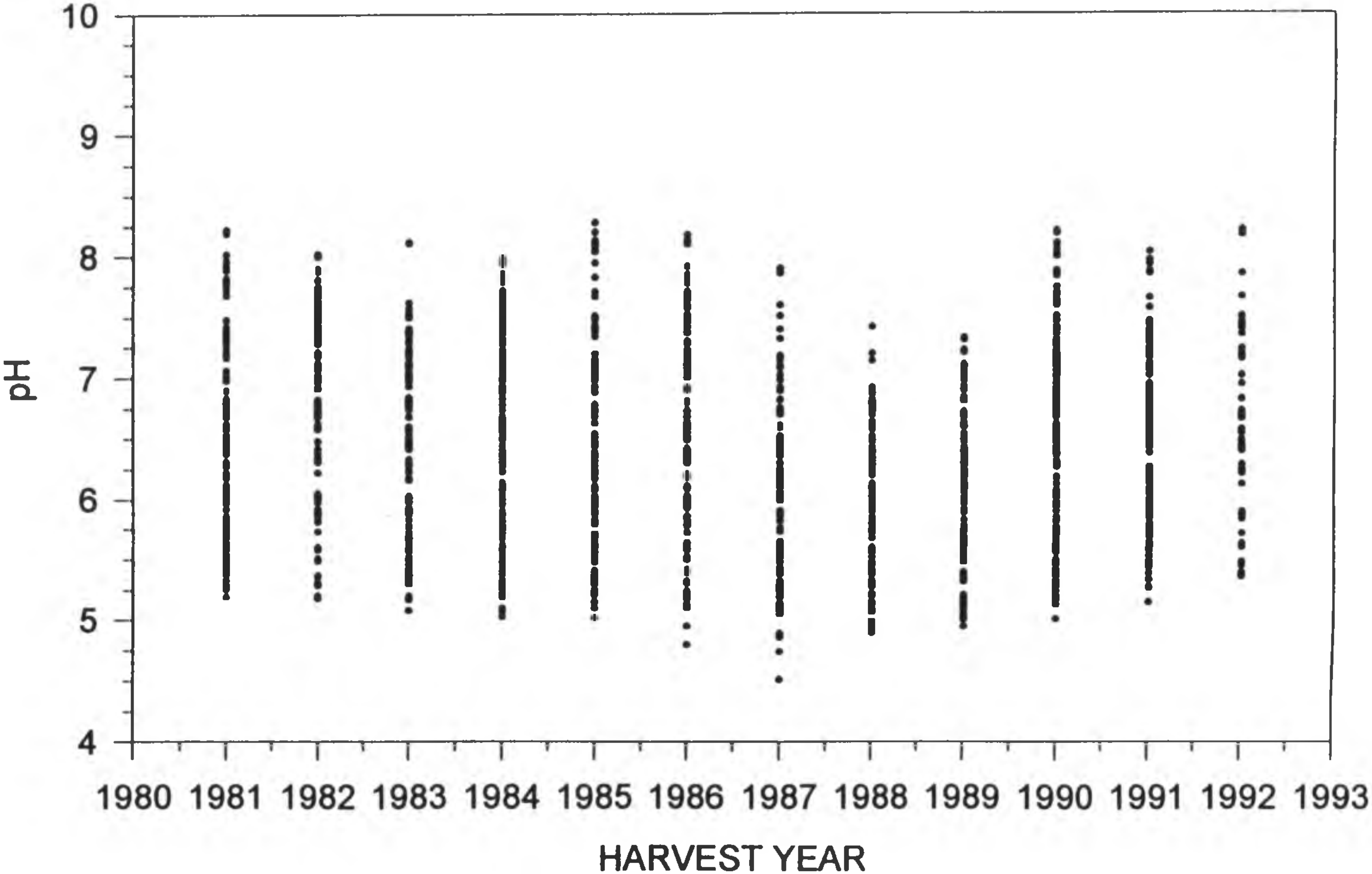


Figure 14. Soil pH data by field from 1981-1992.

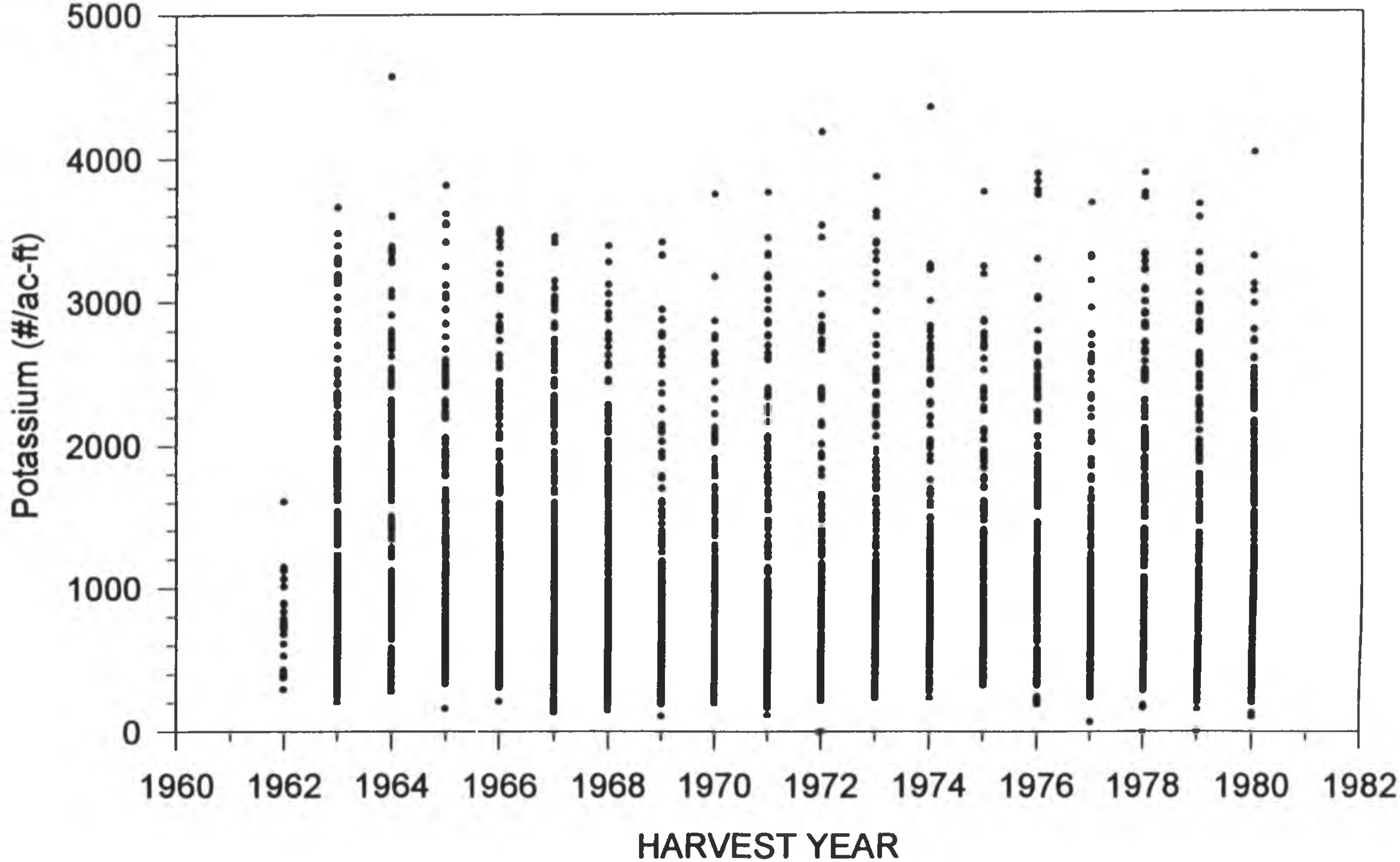


Figure 15. Potassium in pounds per acre-foot by field from 1962-1980. Soil analysis data is collected following harvest.

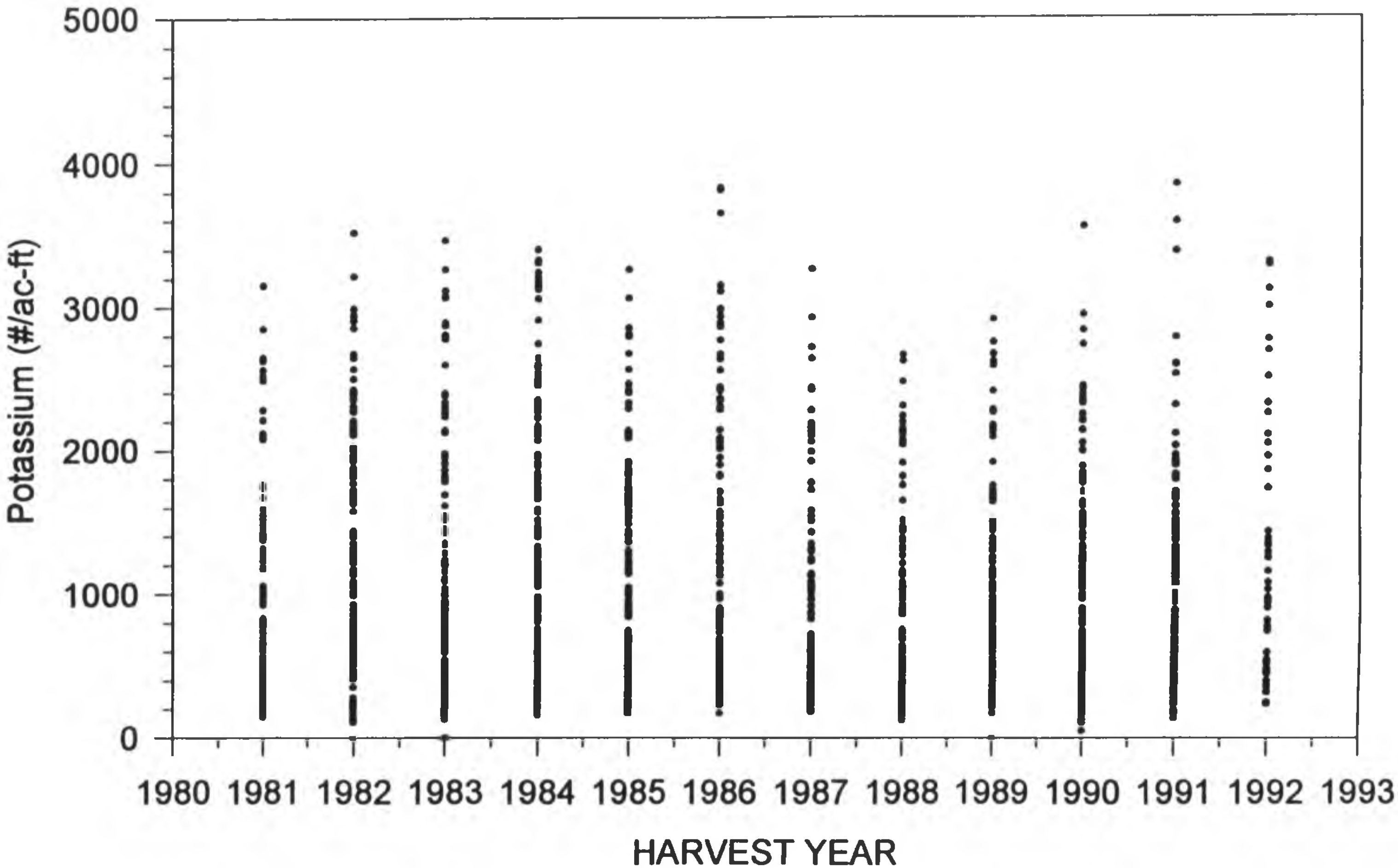


Figure 16. Potassium in pounds per acre-foot by field from 1981-1992. Soil analysis data is collected following harvest.

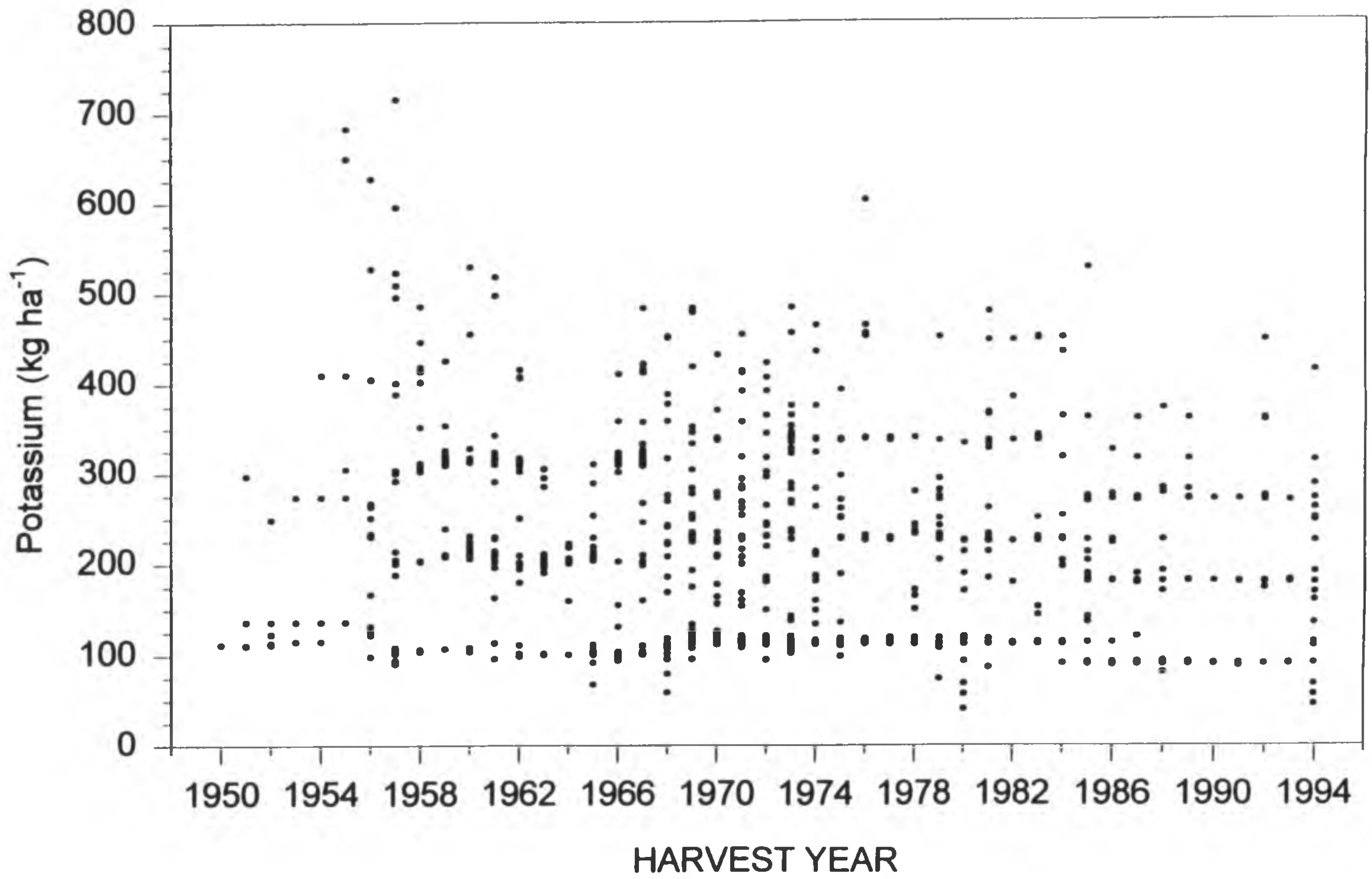


Figure 17. Potassium fertilizer (kg ha^{-1}) applied by field for harvest years 1950-1994.

Map Analysis Methods

Thematic maps (data maps) were made for every two year's data (e.g. TSA 1989-90) for all the variables in the field history and predrip databases to test using maps for data visualization. Maps were also made to contrast the spatial pattern of variables for furrow irrigation with drip irrigation. Legend categories were chosen to follow a normal distrubution. Five legend categories were used for each map to simplify comparisons. Colors or gray scales selected went from light (yellow) for low values to dark (black) for high values with the center category being the largest. If values are continuous in the legend, grey scales or colors should be used that allow the viewer to see the range of values (Monmonier, 1991). It was much more difficult choosing legend categories for percentages (brix, pol, purity, adequacy) which were not normally distributed. Examining 45 years of field history data with so many variables easily resulted in almost 300 data maps being produced using AGISW.

The maps overall were very disappointing to the viewer. In was difficult to see if spatial patterns in the yields reflected spatial patterns in the environment. One problem was that 157 fields are too many to sort out on a page-sized map. On screen it is possible to zoom in on areas to see the map in more detail but with printed maps this is not an option. Another reason is that many relationships are temporal, not simply spatial. Groups of fields by irrigation division (4 groups) or irrigation supervisor (12 groups) were simpler and easier to understand. It may also have been too confusing to plot yields of two different years on one map.

Years are different from one another and plotting two different populations together with differing variability makes the map more difficult to understand.

Figure 18 is a map of mean rainfall by harvest for furrow irrigation. Most of the missing fields (dot pattern) are fields that were added with drip expansion and fields more recently added toward Wailuku Sugar. The rainfall values reflect differences of planting month and age. For cane harvested at two years, dividing rainfall by 2 is a better indication of yearly rainfall. The lowest range (25-39 inches) is equivalent to 635 - 991 mm over two years indicating that much of the plantation is very dry. Irrigation rounds over the entire crop cycle for furrow irrigation are mapped on Fig. 19. Comparing this with the soil moisture storage map (Fig. 12), it can be seen that the areas with the highest soil moisture values receive the fewest irrigation rounds.

Potential evapotranspiration (PE) is included in the field history database. Figure 20 is a map of mean potential evapotranspiration divided by age in months for drip irrigation harvests. The highest PE/month values are found in Maalaea Division followed closely by Keahua Division. The lowest values are in the areas with the most rainfall. The upper two sections of fields with missing data (dot pattern) are mill waste fields not converted to drip.

Mean sugar yields for furrow irrigation are presented in Fig. 21. (To convert tons sugar/acre to tonnes sugar hectare^{-1} multiply by 2.24). The highest furrow yields are on soils with high soil moisture storage and high pH. Maalaea Division has high potential evapotranspiration but low soil moisture storage

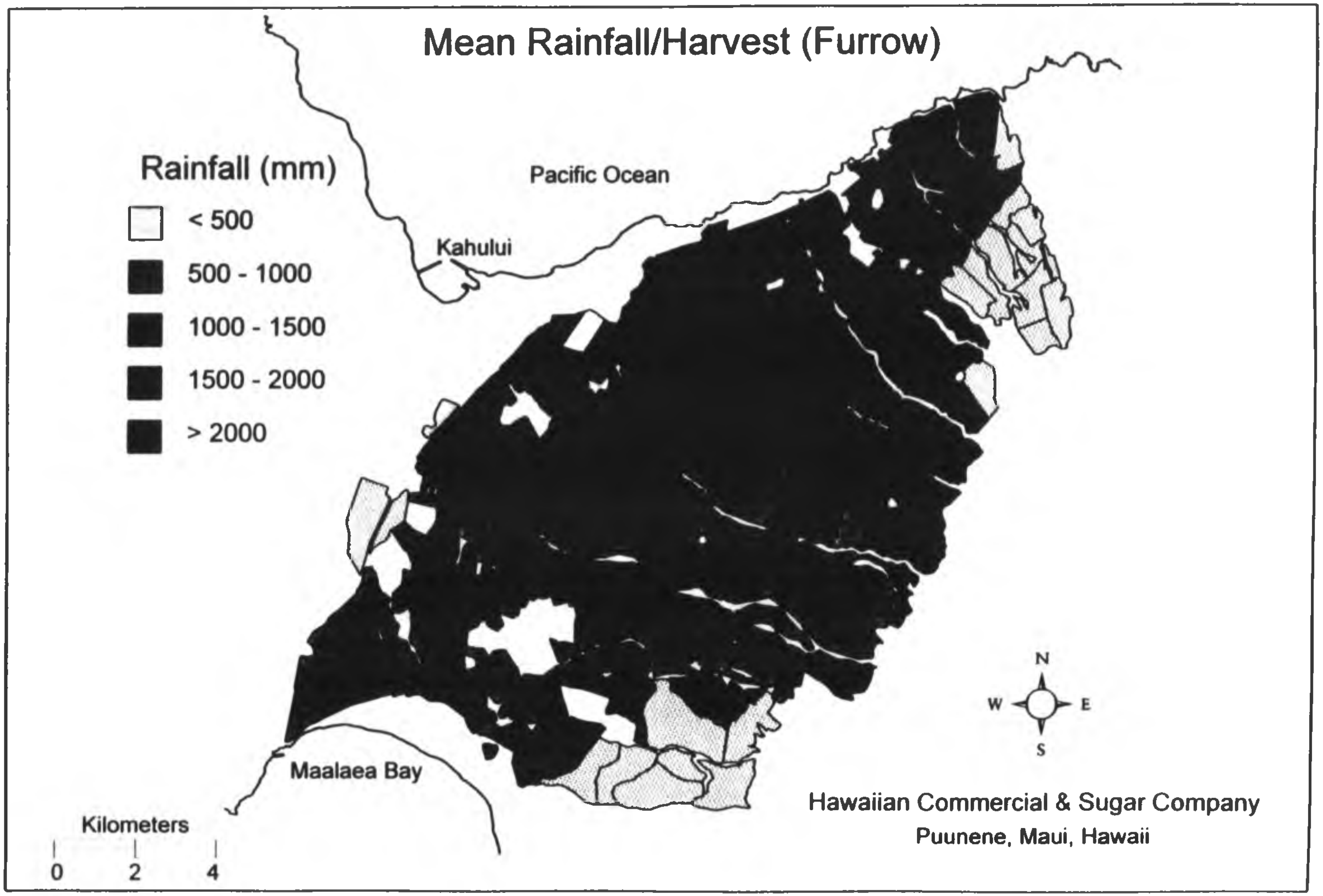


Figure 18. Map of mean rainfall (mm/harvest) with furrow irrigation data.

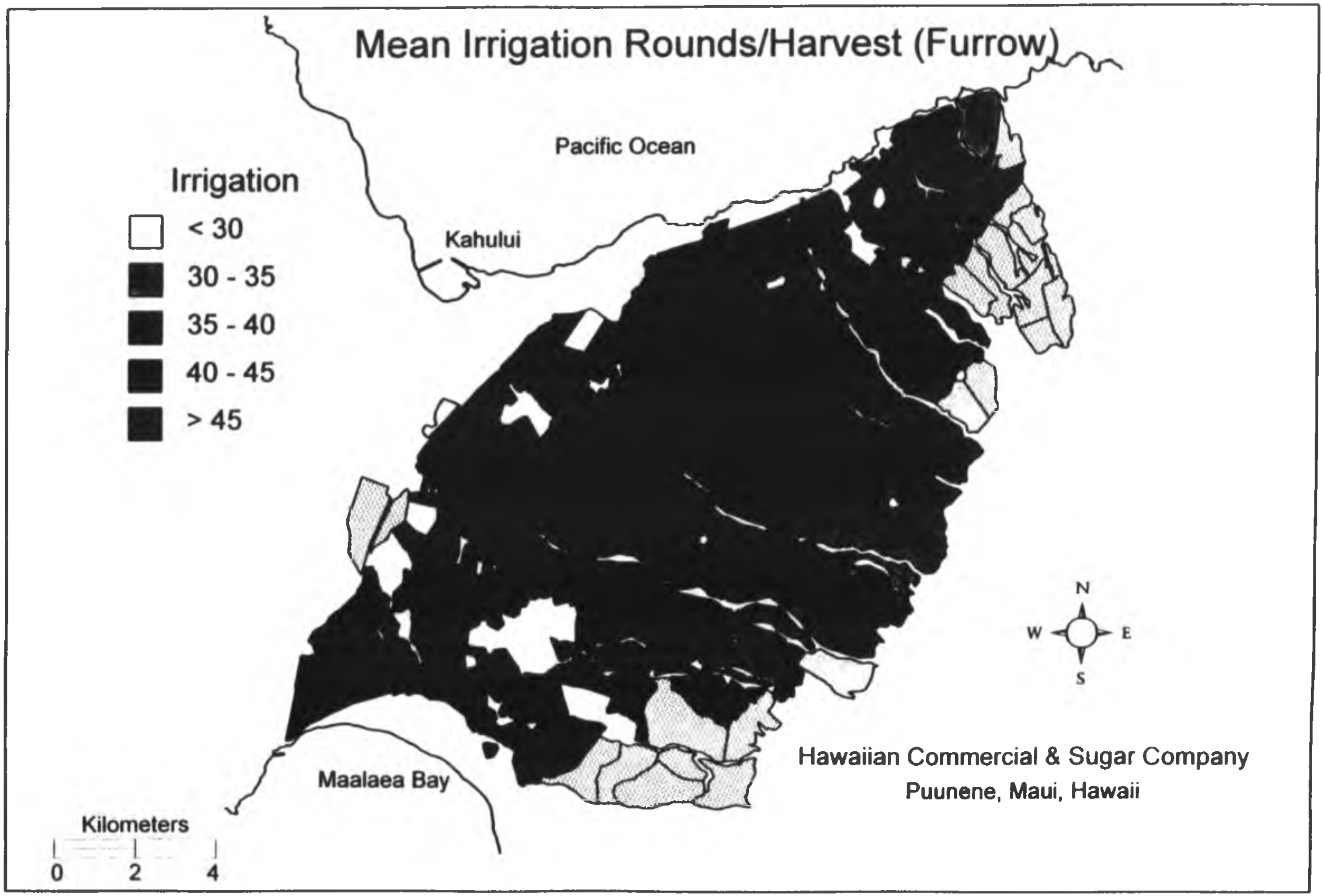


Figure 19. Map of mean irrigation rounds per harvest with furrow irrigation data..

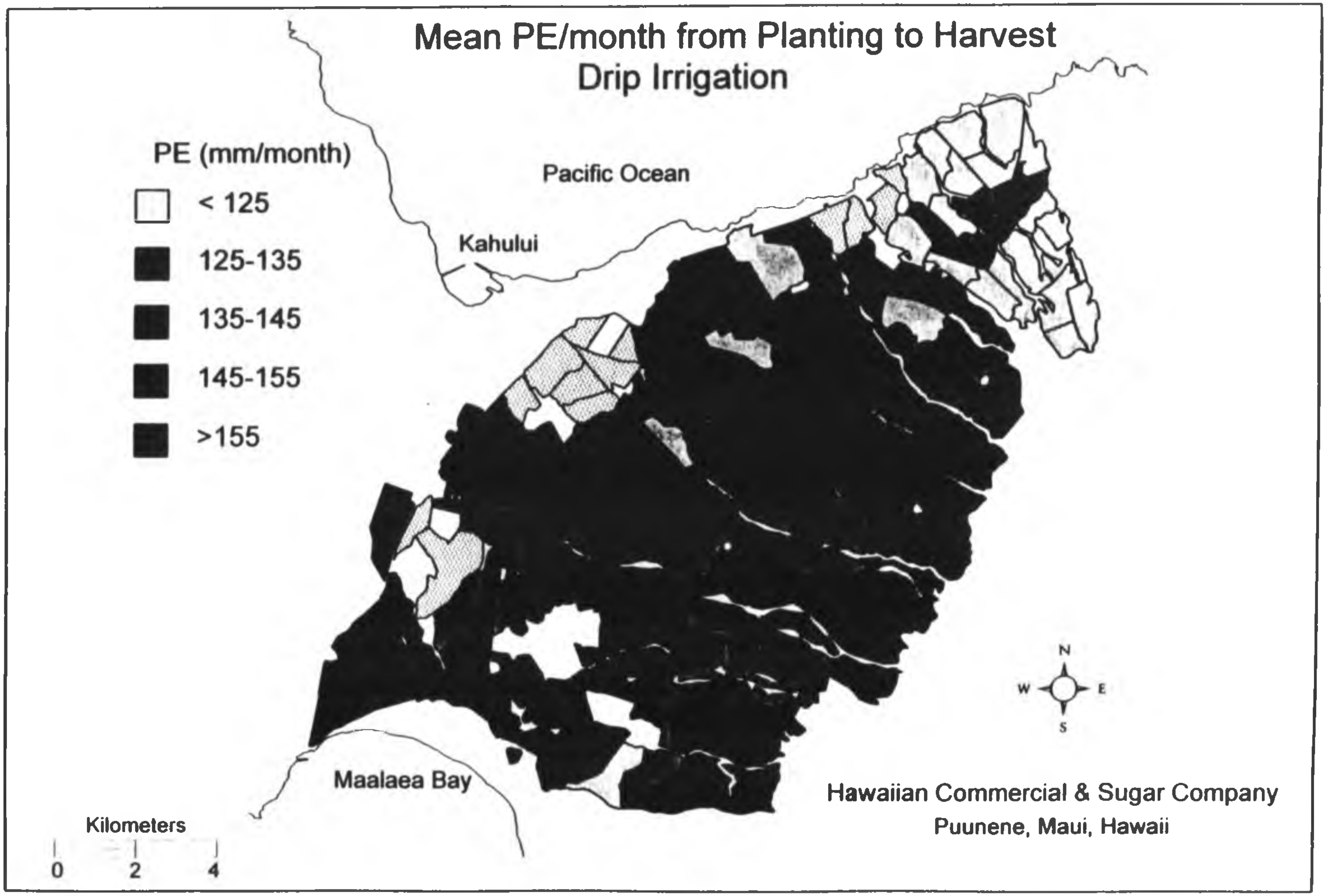


Figure 20. Mean potential evapotranspiration/age (mm/month) with drip irrigation data.

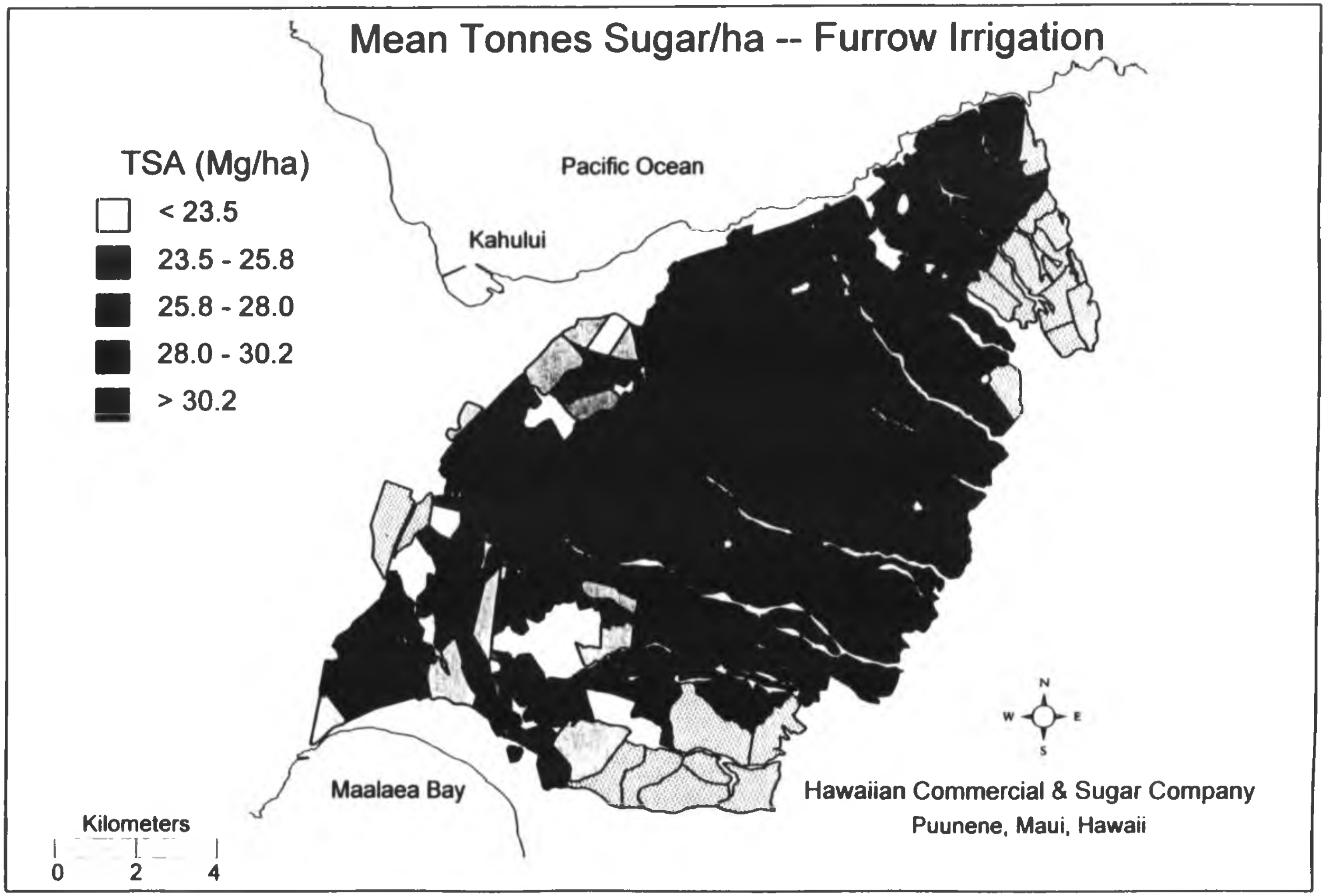


Figure 21. Mean tonnes sugar hectare^{-1} map with furrow irrigation data.

(coarser soils) and relatively low yields. With drip irrigation, soil moisture storage is no longer limiting and the highest yields are in the area with the highest potential evapotranspiration (Fig. 22). Good yields were scattered throughout the plantation. A comparison of mean TSAM (tons sugar acre^{-1} month^{-1}) with furrow irrigation (Fig. 23) and drip irrigation (Fig. 24) also reveals not only the increase in yield following drip conversion but also the spatial shift of the yield pattern.

Table 5 lists the top twenty fields with the highest mean yields (tonnes sugar hectare^{-1}) for both furrow irrigation and drip irrigation. Not only are the yields higher with drip but the change in field numbers indicates spatial change as well. Fields numbered in the 300s and 400s are primarily located in Keahua Division and fields in the 900s are located in Maalaea Division.

The maps did successfully illustrate the importance of planting date and age to yield. When comparisons are made between the spatial pattern of planting month and age with tonnes sugar hectare^{-1}, similarities are evident. Figures 25, 26, and 27 are maps of data from 1987 (a record year) and 1988. The dark areas on Fig. 25 indicate yields were high in many areas of the plantation. Figure 26, a map of the month of planting (START) 1987-1988 indicates that many of the fields were planted in the first 6 months of the year (the legend goes from dark to light as fields because the first half of the year is better for both planting and harvesting). Harvest ages 1987-1988 (Fig. 27) were higher for many fields scattered throughout the plantation. By contrast, yields for 1991-1992 (Fig. 28) were relatively low. Many of the fields, especially at low elevations, were planted later in the year (Fig. 29) and harvest age was particularly low (Fig. 30).

These results led to further exploration of the importance of planting date and age statistically and graphically. Simply mapping the variables is not enough to understand the interaction between space and time in the complicated harvest schedule. Because sugarcane is a two-year crop in Hawaii, every year the pattern of planting and harvest is different from the year before. Each harvest reflects not only the field's physical characteristics but also interactions with the environment.

As a example of the difference timing can make, rain is beneficial when the crop needs water but it can be harmful if it interferes with harvesting. Sunshine is beneficial if water is not limiting but can add to stress if it is. Fields with actively growing sugarcane and sufficient water will benefit most by increased solar radiation in the summer months.

Also of interest in map analysis were maps with fields aggregated by their pan (evaporation) assignments, key station (rain) assignments, and soil moisture storage. These maps illustrate how spatial information is entered into the water balance. Mapping the fields using these groups as variables is a way to check for assignment errors. For example, maps make it easy to spot errors if a field has been assigned to a weather station it is nowhere near. These assignments are the key to water balance input. If not accurate, output will be affected. How fields are assigned to irrigation supervisors is the key to output. Errors affecting irrigation scheduling can also affect sugarcane yield.

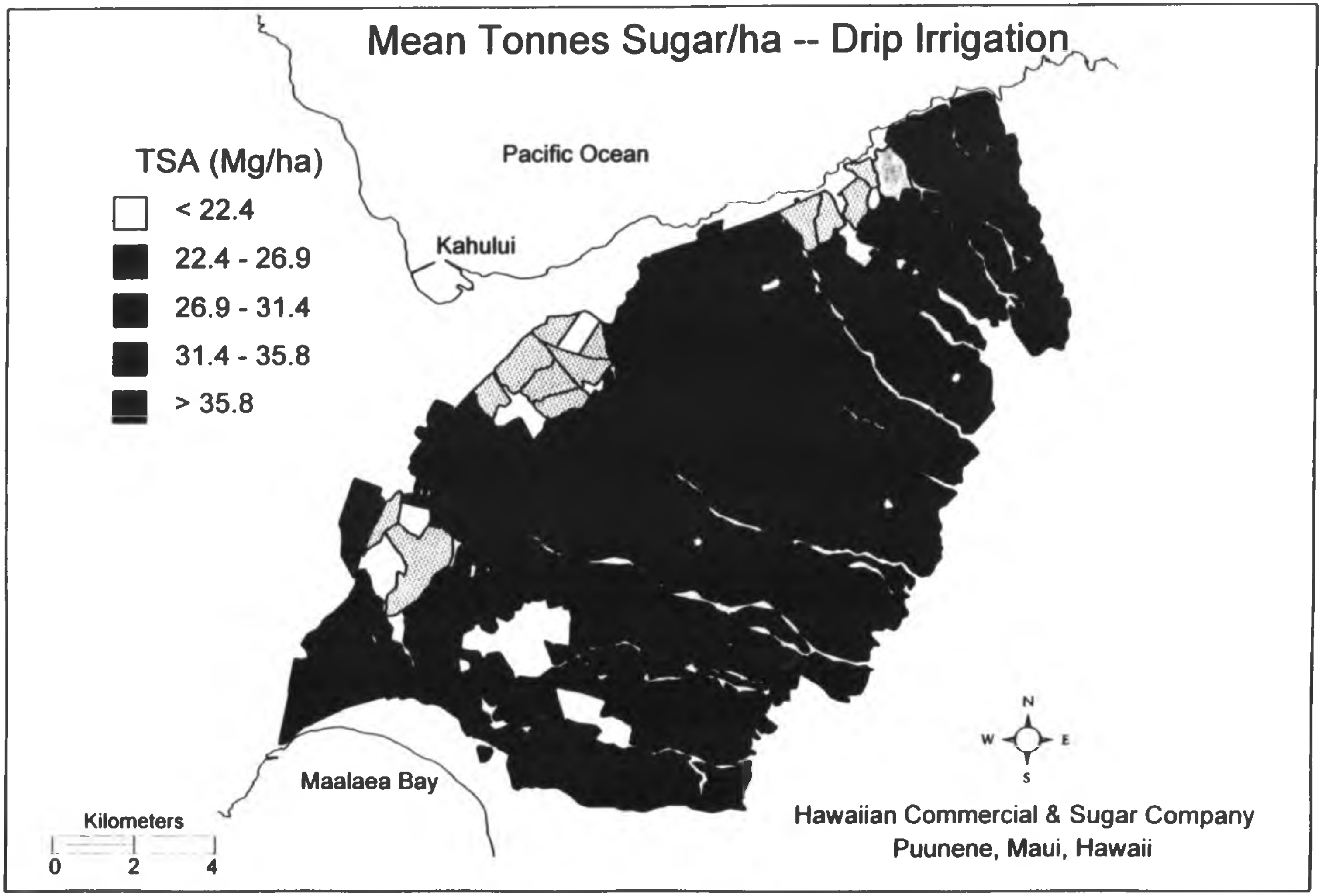


Figure 22. Mean tonnes sugar hectare^{-1} map with drip irrigation data.

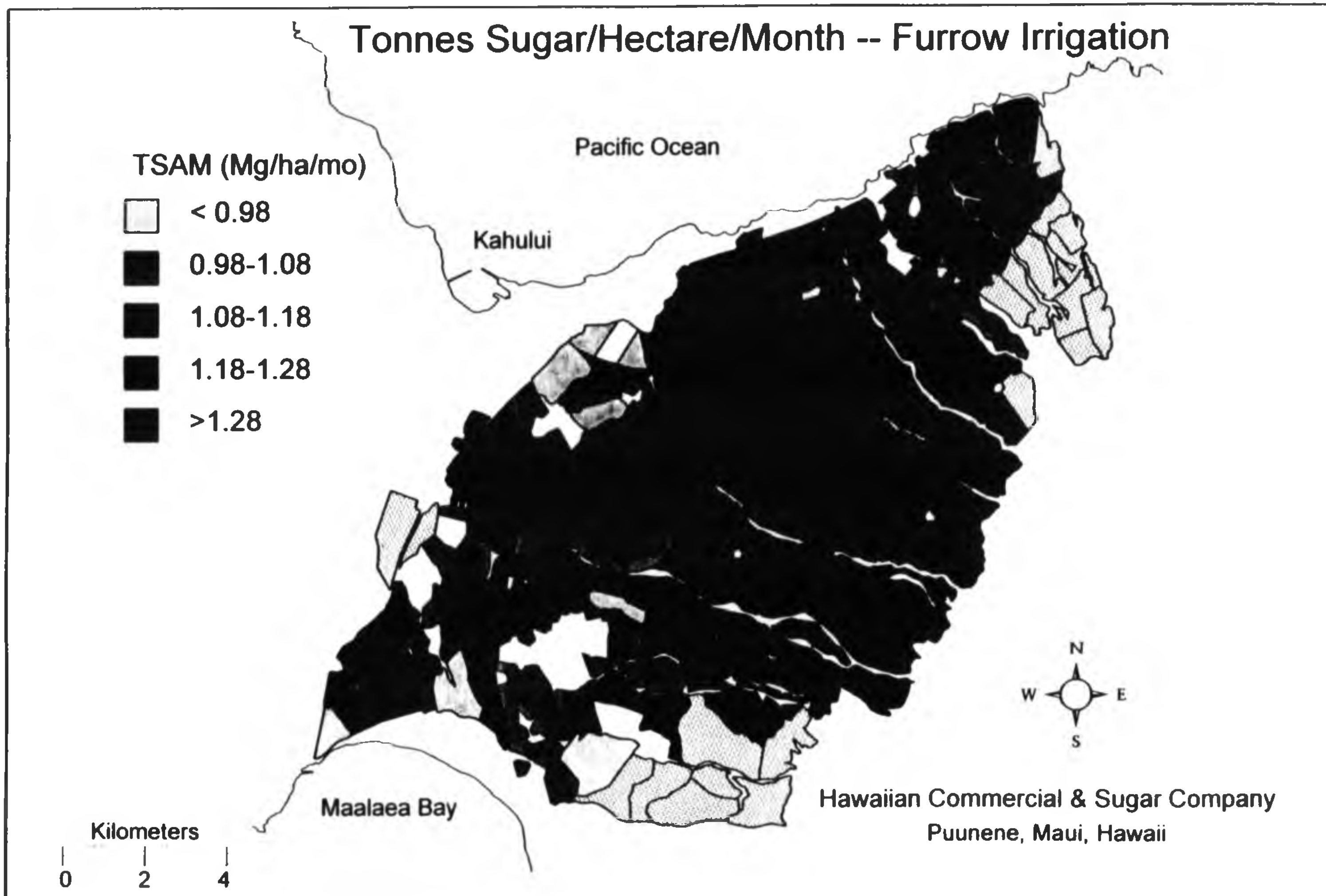


Figure 23. Mean tonnes sugar hectare^{-1} month^{-1} map with furrow irrigation data.

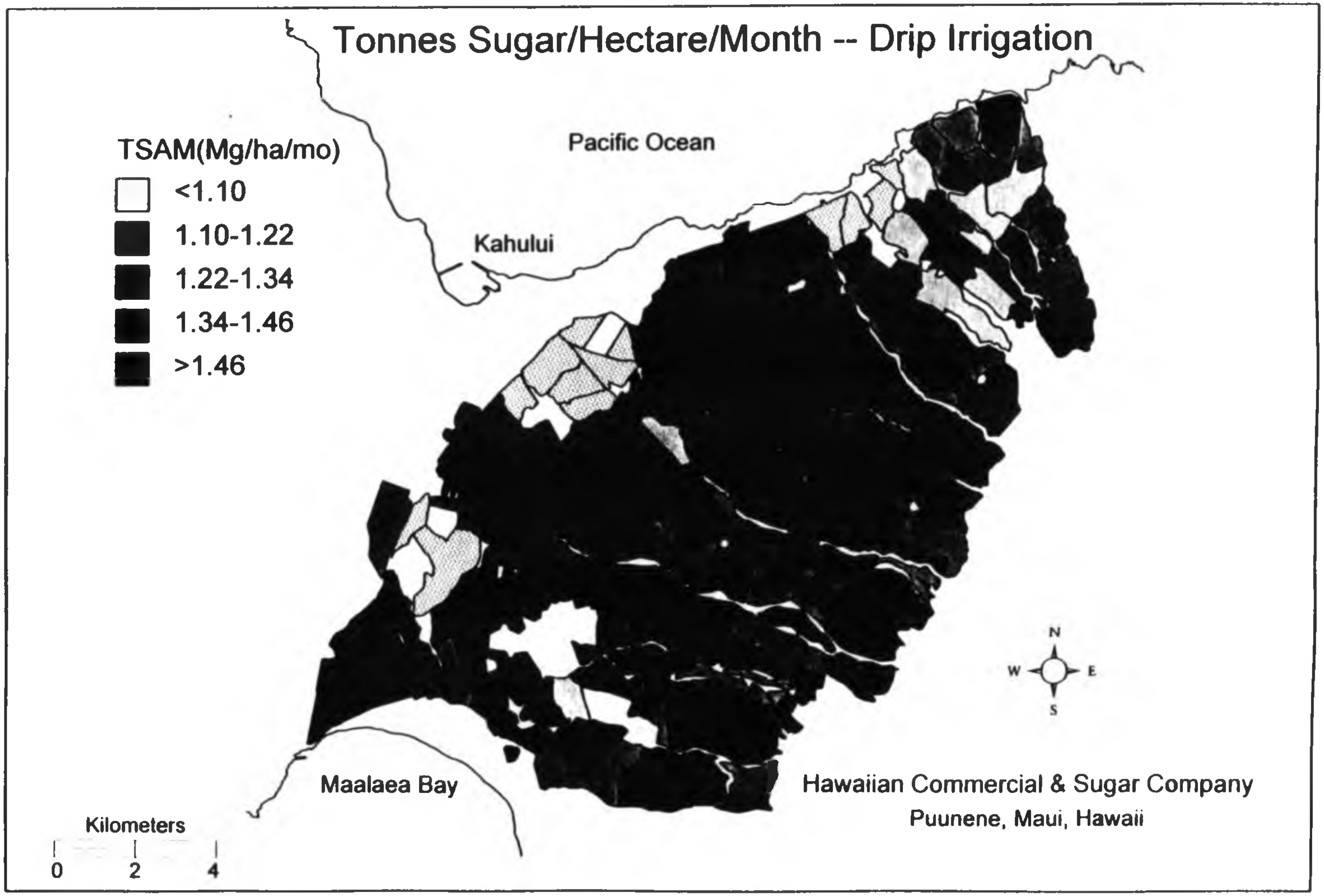


Figure 24. Mean tonnes sugar hectare^{-1} month^{-1} map with drip irrigation data.

Table 5. The twenty fields with the highest mean sugar yields (TSA in Mg ha^{-1}) for both furrow and drip irrigation.

---Furrow Irrigation---			---Drip Irrigation---		
Field	n	Yield*	Field	n	Yield*
307	11	32.97	904	2	39.68
313	7	31.65	902	2	37.15
312	8	31.53	908	4	36.77
403	13	31.45	913	4	36.13
401	13	31.00	717	4	36.11
302	15	30.56	905	5	35.13
310	13	30.31	715	5	35.09
409	13	30.43	418	5	35.00
408	14	30.22	213	4	34.93
400	13	30.18	501	7	34.83
715	17	30.11	719	2	34.81
500	17	30.00	809	6	34.44
501	13	29.86	209	6	34.36
300	16	29.73	900	5	34.27
801	13	29.33	413	8	34.21
406	13	29.61	509	8	34.12
301	13	29.59	916	4	34.05
716	17	29.53	907	4	33.90
413	10	29.14	818	6	33.89
805	16	29.07	312	7	33.69

*Means were ranked using Duncan's Multiple Range Test and not found to be significantly different at the 0.05% level for each irrigation type but space does not allow listing all the fields and corresponding letters.

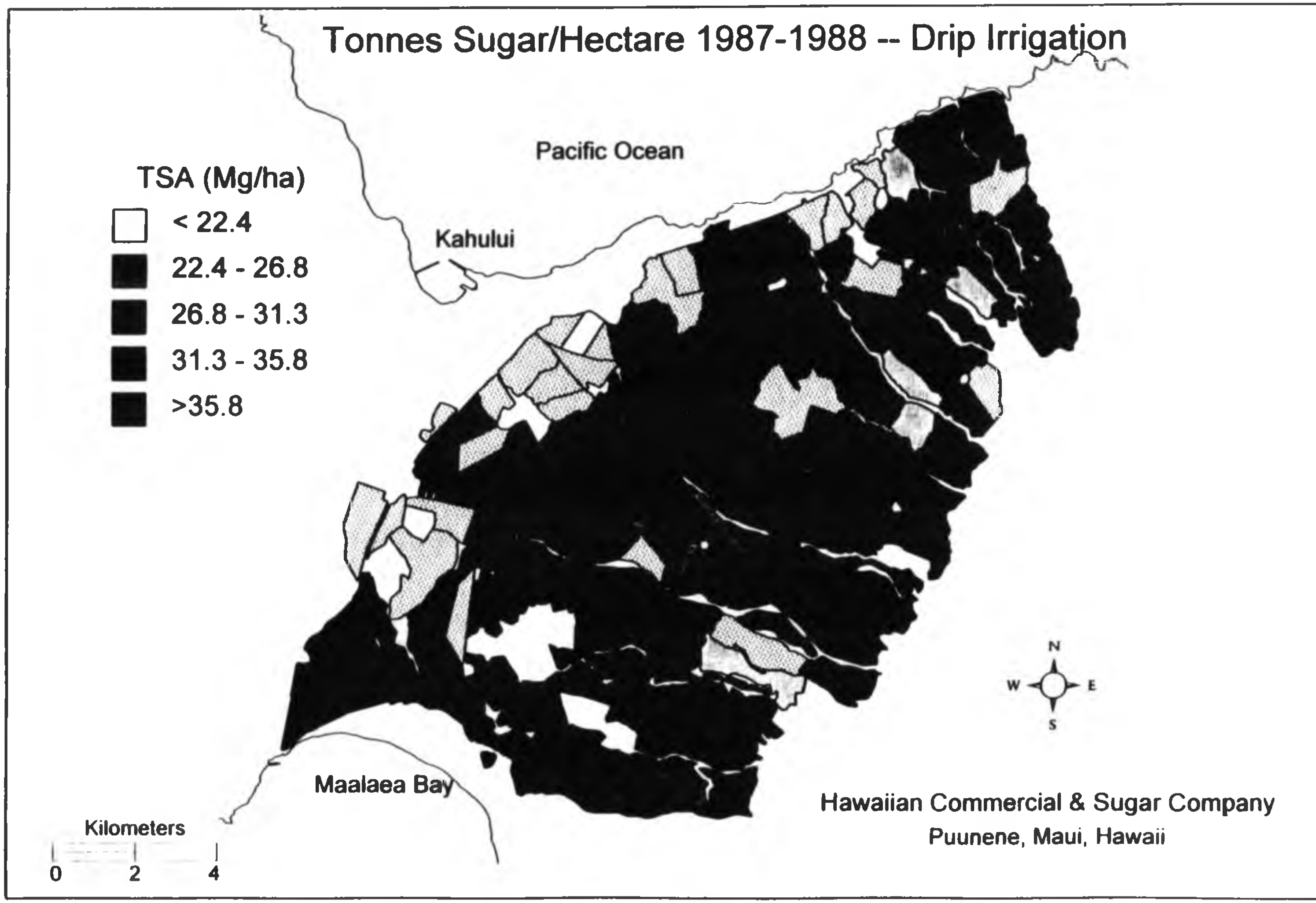


Figure 25. Map of tonnes sugar hectare^{-1} for fields harvested in 1987 and 1988.

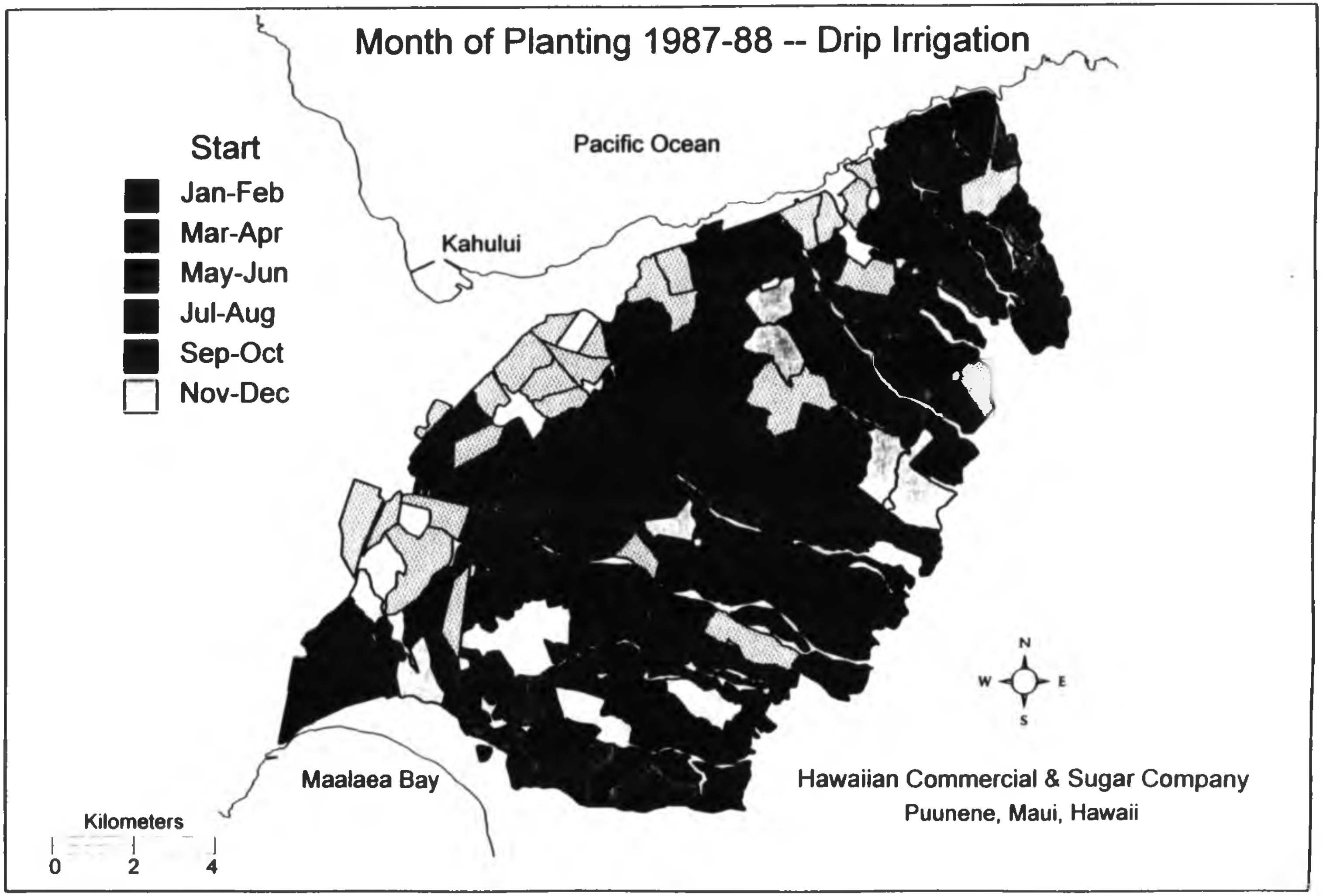


Figure 26. Map of planting month for fields harvested in 1987 and 1988.

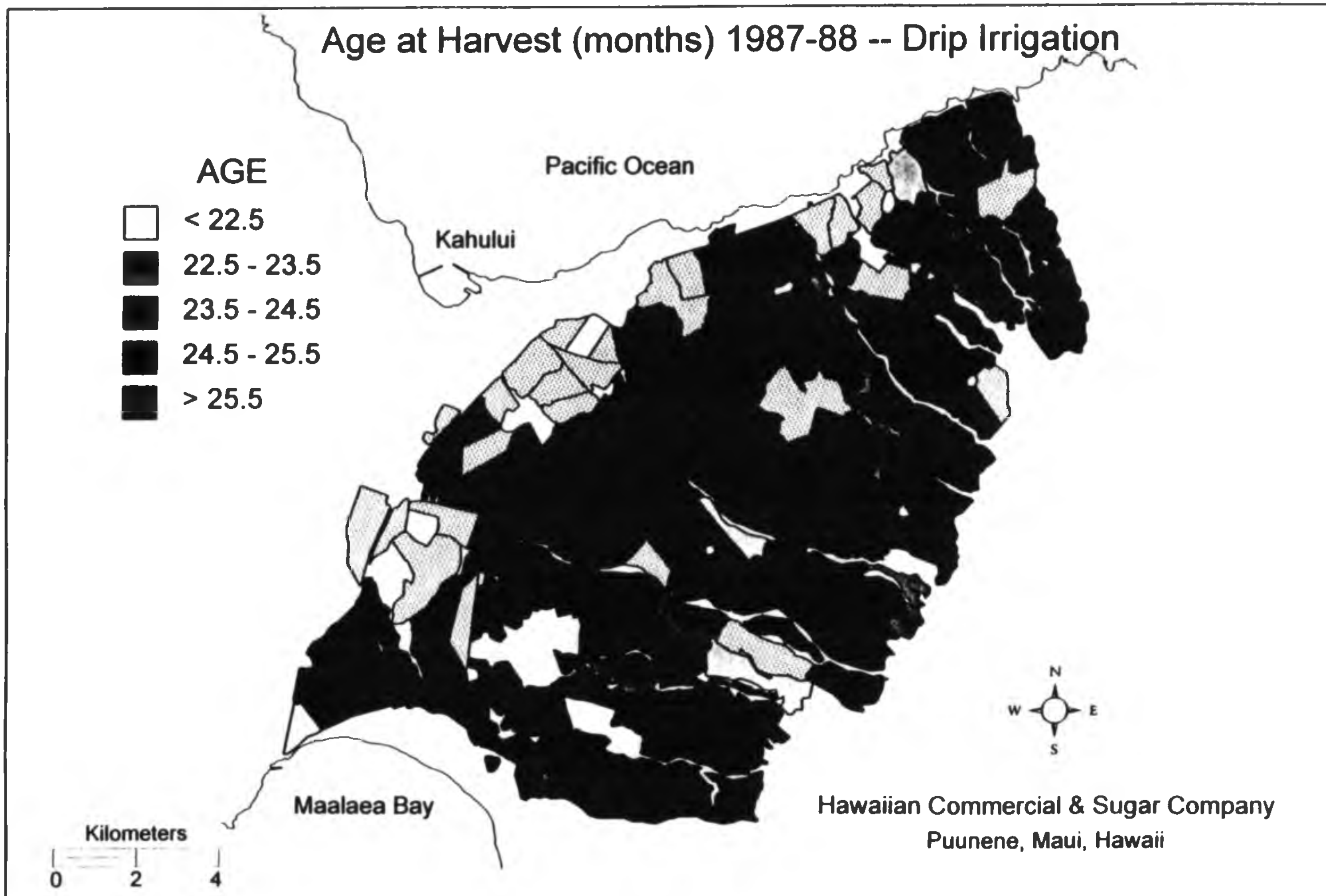


Figure 27. Map of age (months) at harvest for fields harvested in 1987 and 1988.

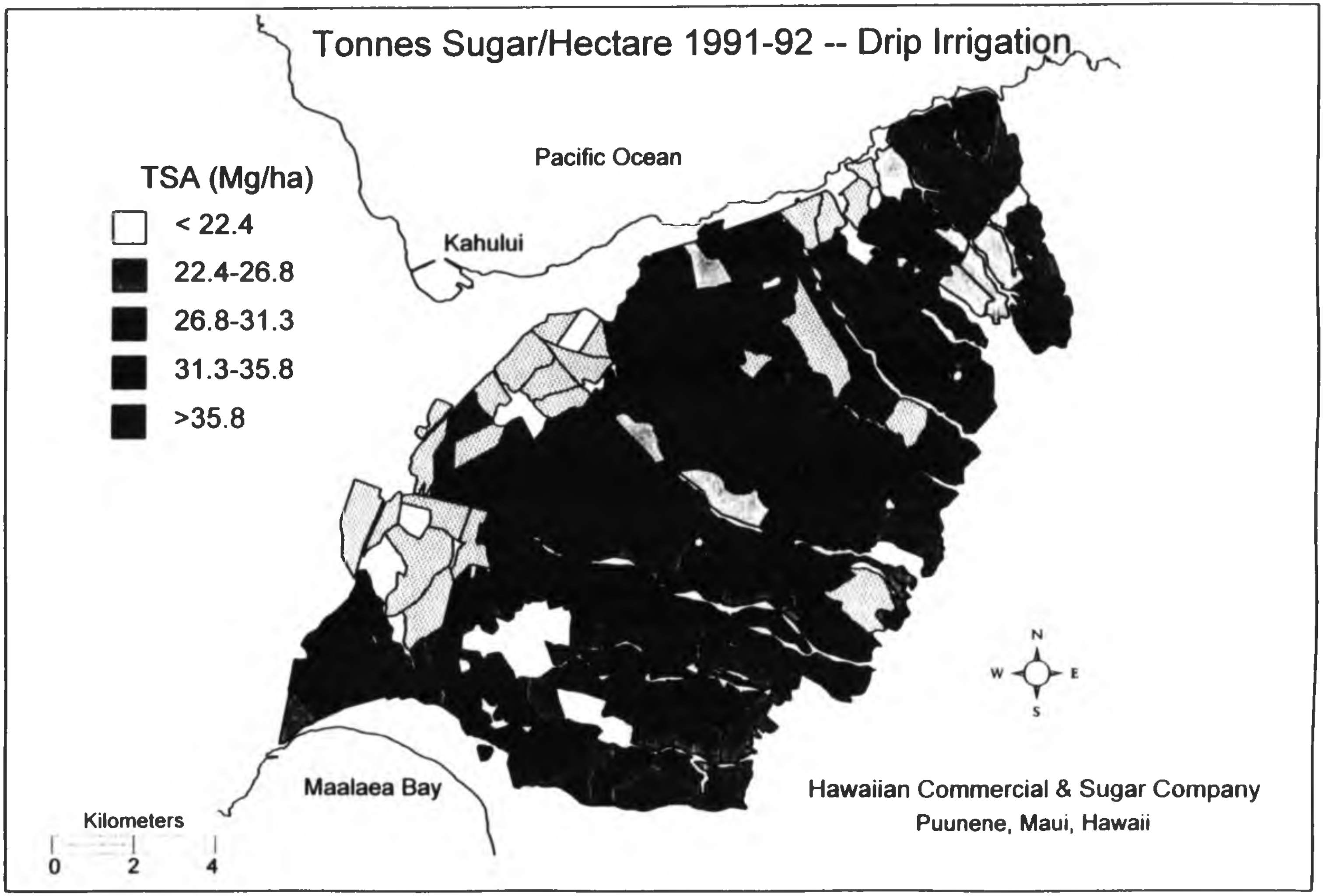


Figure 28. Map of tonnes sugar hectare^{-1} for fields harvested in 1991 and 1992.

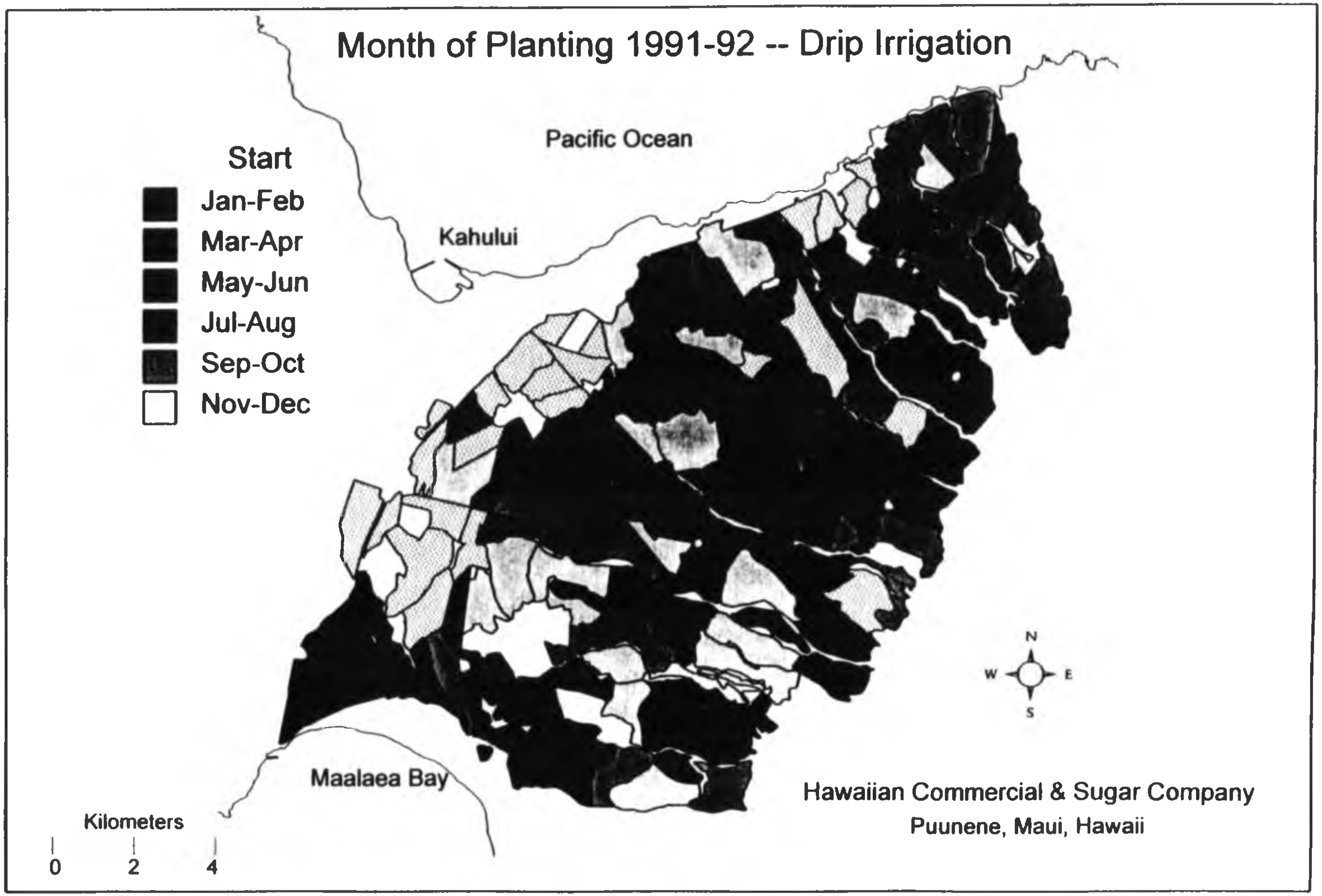


Figure 29. Map of planting month for fields harvested in 1991 and 1992.

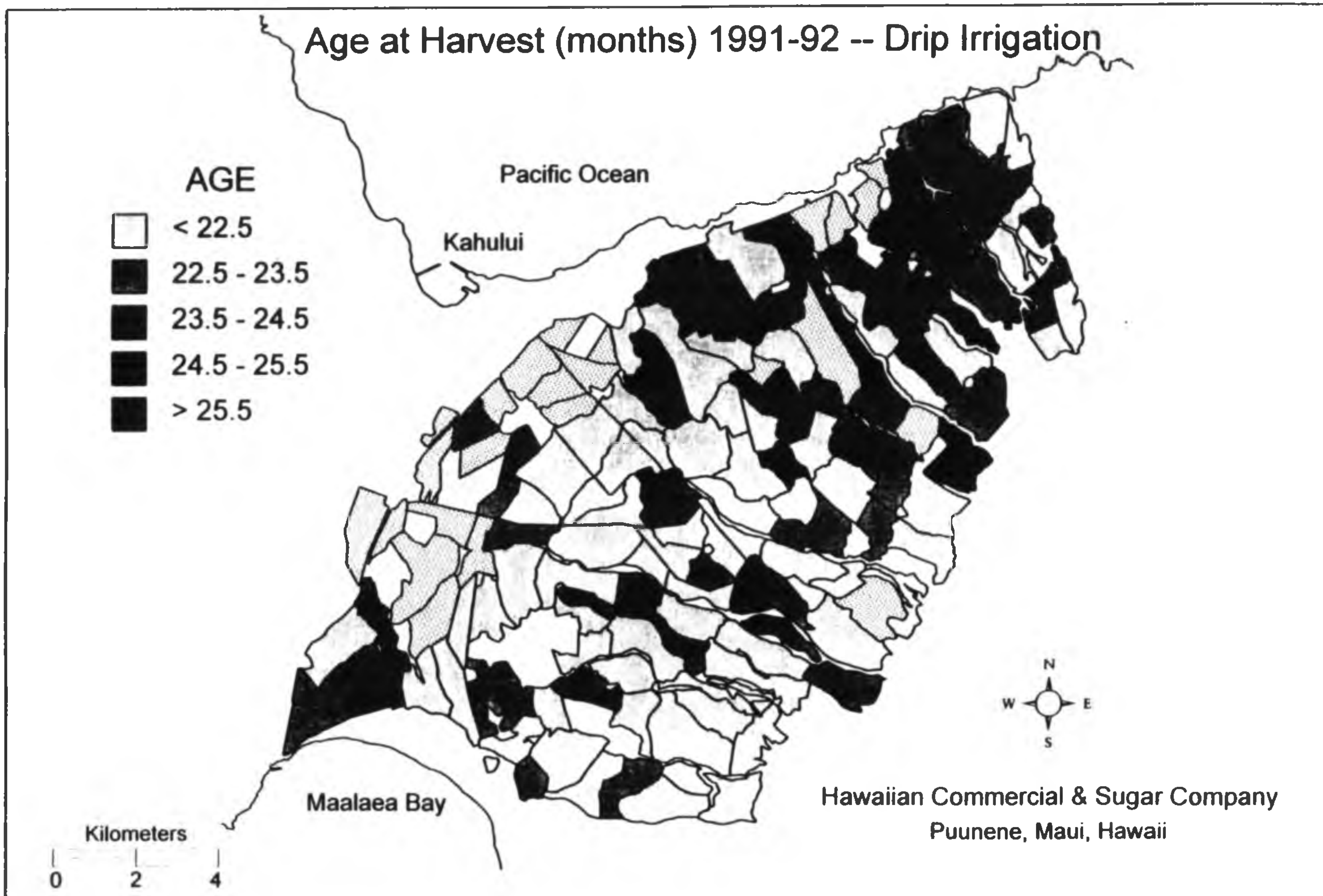


Figure 30. Map of age (months) at harvest for fields harvested in 1991 and 1992.

Planting Month and Harvest Age

The apparent precedence of temporal factors over spatial ones in the preceding map analysis was tested graphically and with univariate and multivariate statistics. Using a combination of methods is one way to make sure that effects are not just artifacts of a particular method and also a way to view variability from different angles. With a 24-month crop, harvest month and planting month are so closely correlated that their effects are not easy to sort out. Effects of planting month may actually be harvest effects and vice versa.

Table 6 lists furrow irrigation mean tonnes sugar hectare^{-1} for different harvest age groups. (The age groups were originally used in a map legend. For consistency, these same groups are used as classes in statistical analysis.) The highest yields are for sugarcane 24.5 months of age and above (groups 4 and 5). The largest group of sugarcane (625 harvests) was harvested around 24 months of age (group 3). The lowest yields are from cane at less that 22.5 months of age.

Means for the same age groups but with drip irrigation data are given in Table 7. Mean tonnes sugar hectare^{-1} is highest for cane over 24.5 months of age as it was with furrow irrigation. Again, the most harvests (261) are in the age group 23.5 to 24.5 months and the lowest yields are from cane less than 22.5 months of age..

Duncan's Multiple Range Test was used to rank mean yields by planting month (START) for both furrow and drip irrigation. Table 8 is a ranking of mean tonnes sugar hectare^{-1} for furrow irrigation. The number of harvests (n) is lowest

Table 6. Furrow irrigation mean sugar yields (TSA in Mg ha^{-1}) for different harvest age groups.

Group	Age	n	Yield*
	---months---	---harvests---	---Mg ha^{-1}---
5	>25.5	387	27.84a
4	24.5 - 25.5	259	27.57ab
3	23.5 - 24.5	625	27.07bc
2	22.5 - 23.5	498	26.65c
1	< 22.5	278	24.01d

*Means followed by the same letters are not significantly different at the 0.05 % probablility level by Duncan's Multiple Range Test.

Table 7. Drip irrigation mean sugar yields (TSA in Mg ha^{-1}) for different harvest age groups.

Group	Age	n	Yield*
	---months---	---harvests---	---Mg ha^{-1}---
5	>25.5	154	33.02a
4	24.5 - 25.5	184	32.21a
3	23.5 - 24.5	261	30.95b
2	22.5 - 23.5	154	28.76c
1	< 22.5	133	26.71d

*Means followed by the same letters are not significantly different at the 0.05 % probablility level by Duncan's Multiple Range Test.

Table 68. Drip irrigation yearly mean harvest age (months).

Year	n	Age
	--harvests--	--months--
1980	24	27.10a
1982	32	26.21b
1983	43	25.82bc
1981	32	25.25cd
1979	18	25.23cd
1984	55	25.00de
1988	68	24.61def
1987	65	24.56def
1989	72	24.46def
1985	61	24.38ef
1994	68	24.02fg
1986	61	24.01fg
1993	73	23.83fg
1978	13	23.23gh
1990	69	22.87h
1992	64	22.75h
1991	71	22.02i

*Means followed by the same letters are not significantly different at the 0.05 % probability level by Duncan's Multiple Range Test.

for the winter months November, December, January, and February when winter rains can interfere with harvest operations. The best yields are from cane planted January through July for both furrow and drip irrigation (Figs. 31-32). August and September follow in rank. The worst planting months are October, November, and December. A comparison of means by harvest month will be presented later in this section.

Figure 33 is a graph of the same furrow yield data as Fig. 31 except that tonnes sugar hectare^{-1} has been divided by harvest age to create the variable TSAM (tonnes sugar hectare^{-1} month^{-1}). Again the origin is not zero on the y-axis. Adjusting by age does not change the pattern very much. January has fewer harvests but the highest yield. The best yields are from January to August with September to December the lowest, very similar to TSA. Figure 34 shows a similar pattern for drip irrigation.

PE by harvest is not available for furrow irrigation, but Fig. 35 of mean furrow irrigation rounds by month of planting indicates that summer plantings do not use as much water. This may be because newly planted cane or ripening cane does not require as much water as a full canopy of cane does. Cane planted in winter and early spring is better developed by summer. Higher water use is an indication that growth is occurring when there is a more solar radiation.

In Table 9, mean tonnes sugar hectare^{-1} is ranked by planting month for drip irrigation harvests. The highest drip yields are from cane planted from February to July followed by July, August and January. As with furrow, the

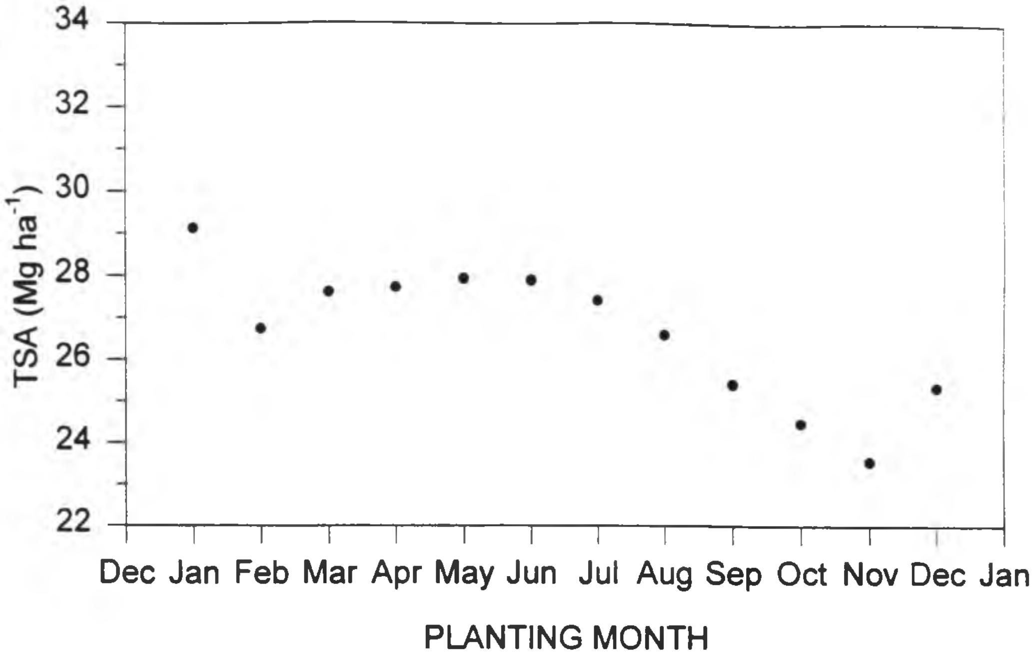


Figure 31. Furrow irrigation mean tonnes sugar hectare^{-1} (TSA) by planting month (START).

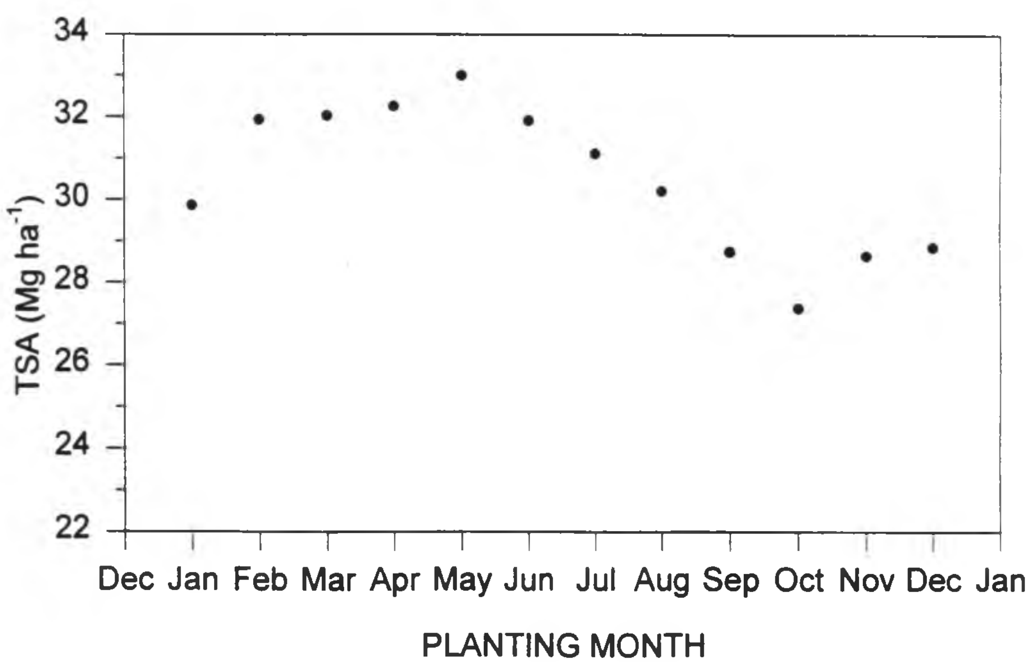


Figure 32. Drip irrigation mean tonnes sugar hectare^{-1} (TSA) by month of planting.

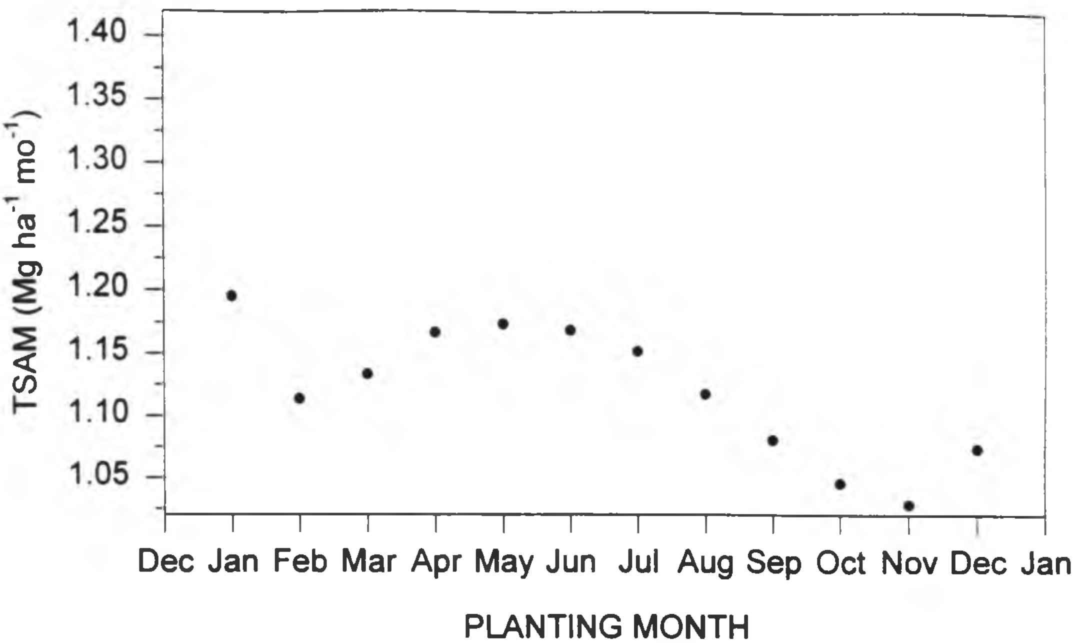


Figure 33. Furrow irrigation mean tonnes sugar hectare^{-1} month-1 (TSAM) by planting month (START).

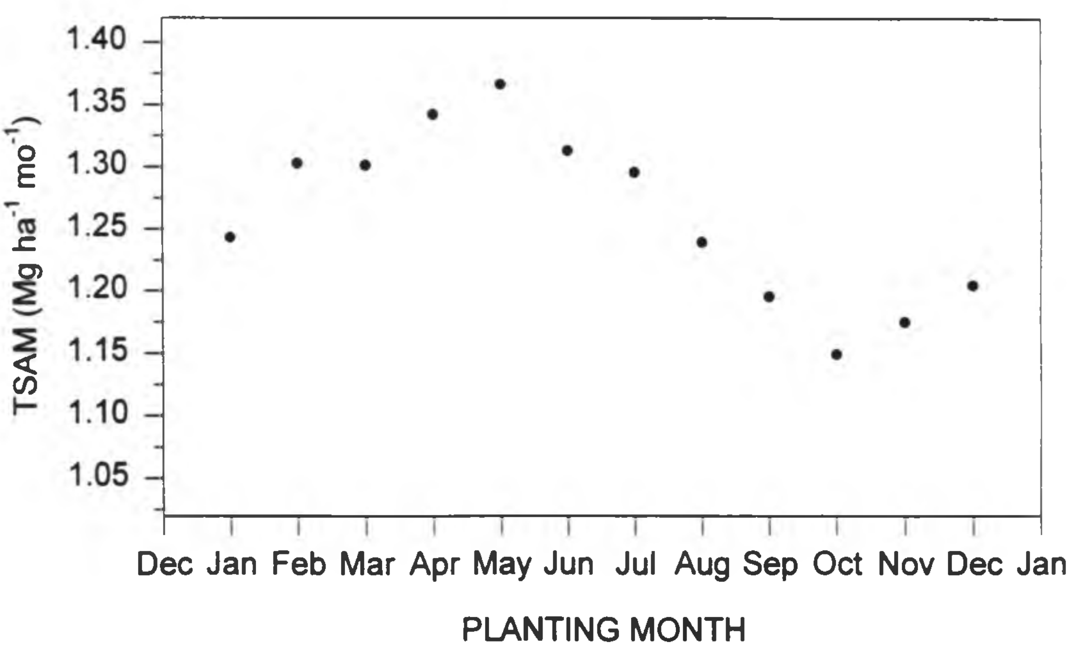


Figure 34. Drip irrigation mean tonnes sugar hectare^{-1} month^{-1} (TSAM) by month of planting.

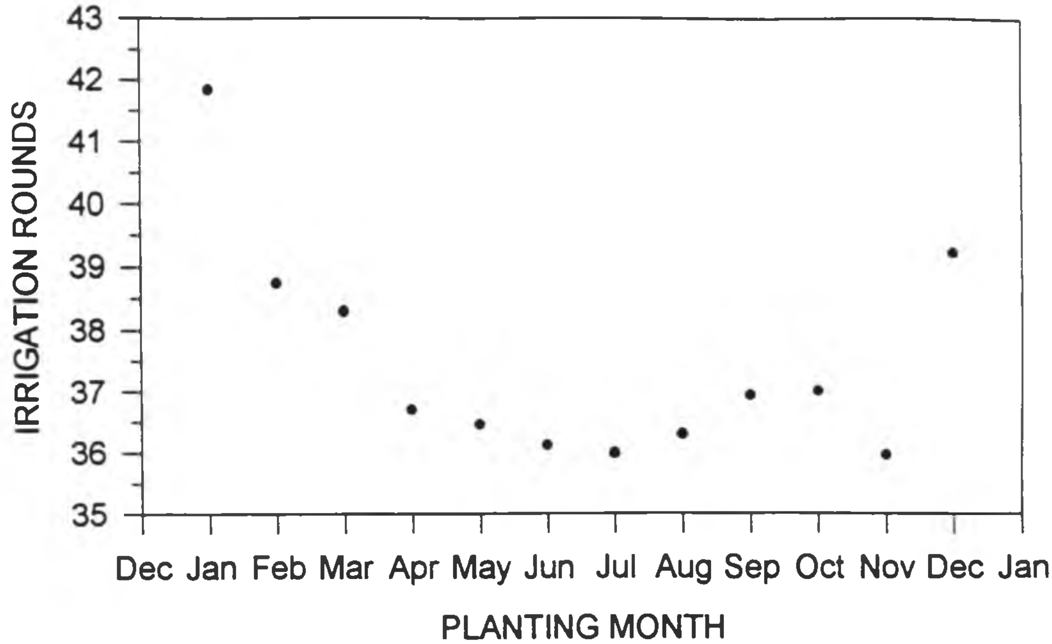


Figure 35. Furrow irrigation mean irrigation rounds by planting month.

Table 9. Drip irrigation sugar yield (TSA in Mg ha^{-1}) by month of planting (START).

Start	n	Yield*
--month--	--harvests--	--Mg ha^{-1}--
May	112	33.00a
April	80	32.26ab
March	43	31.03ab
February	28	31.93ab
June	93	31.91ab
July	116	31.11bc
August	90	30.21cd
January	39	29.87cd
December	43	28.85de
September	96	28.75e
November	59	28.65e
October	90	27.37e

*Means followed by the same letters are not significantly different at the 0.05 % probability level by Duncan's Multiple Range Test.

lowest yields are in September to December. Mean tonnes sugar hectare^{-1} by planting month is plotted in Fig. 32. The y-axis origin is not at a zero and the yields are much higher than they were for furrow (27 to 33 tonnes sugar hectare^{-1}). Figure 34 shows a similar pattern when tonnes sugar hectare^{-1} is divided by age, showing that age is not very different by planting month.

Mean potential evaporation (drip) accumulated over the 24 months from planting to harvest was ranked by planting month. The means with the highest ranking are February to May. According to Clements (1980) cooler temperatures in the spring are better for ripening cane. High PE suggests that cane planting in the spring also is taking advantage of the increase in solar radiation in the summer months. Otherwise there would not be such a yield reponse to high potential evapotranspiration. Figure 36 shows that cane planted in September and October has the lowest PE.

Cane planted in May, September, October, and November was harvested somewhat earlier according to the ranking of harvest age by planting month for furrow irrigation (Table 11). The means are plotted on in Fig. 38. For drip irrigation (Table 12) there are no significant differences between mean harvest ages for the different planting months. Figure 39 is misleading as the range of age on the y-axis is smaller than Fig. 38, exaggerating the difference between means.

To show the tremendous overlap between harvest month and planting month, harvest month by planting month (furrow irrigation) is plotted in Fig. 40. From March to October there is almost a 1:1 relationship between the two. While

Table 10. Drip irrigation potential evapotranspiration for entire two-year crop cycle by month of planting (START).

Start	n	PE*
--month--	--harvests--	--mm--
April	79	3608.72a
March	43	3575.40a
February	28	3526.88ab
May	112	3421.04abc
January	39	3355.66bcd
December	43	3341.58bcd
June	92	3299.01cd
November	59	3286.80cde
July	114	3210.02de
August	90	3209.97de
September	95	3094.50ef
October	89	3014.38f

*Means followed by the same letters are not significantly different at the 0.05 % probability level by Duncan's Multiple Range Test.

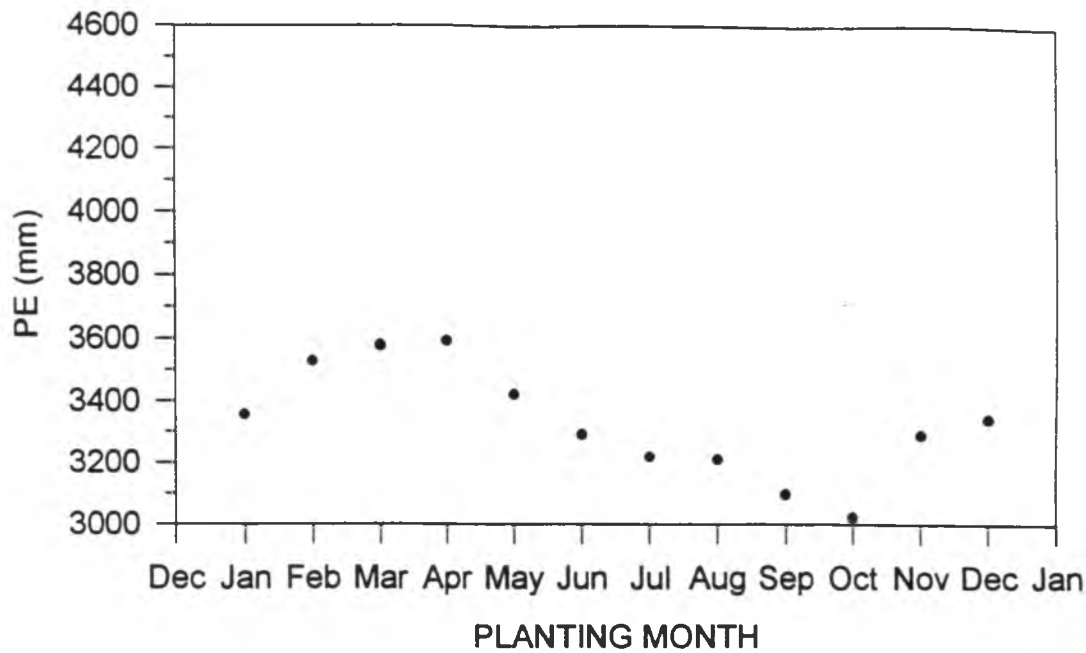


Figure 36. Drip irrigation mean potential evapotranspiration (mm) by planting month.

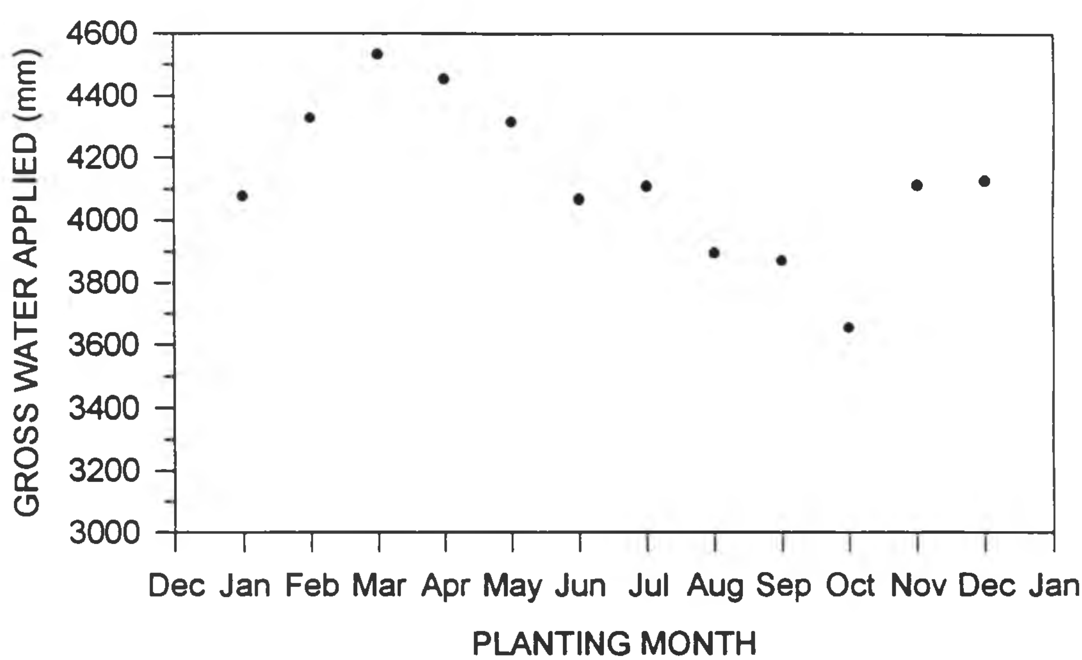


Figure 37. Drip irrigation means gross water applied (mm) by month of planting.

Table 11. Furrow irrigation harvest age by month of planting (START).

Start Month	n	Age*
	--harvests--	--months--
January	22	24.55a
March	147	24.47ab
February	54	24.31ab
December	13	24.06abc
June	233	24.04abc
April	170	23.97abc
July	273	23.94abc
August	269	23.88abc
May	245	23.85abcd
September	265	23.73bcd
October	193	23.42cd
November	50	23.19d

*Means followed by the same letters are not significantly different at the 0.05 % probability level by Duncan's Multiple Range Test.

Table 12. Drip irrigation age in months at harvest by month of planting (START).

Start Month	n	Age*
	--harvests--	--months--
March	43	24.60a
February	28	24.54a
November	59	24.46a
August	90	24.42a
June	93	24.34a
May	112	24.16a
December	43	24.10a
July	116	24.05a
April	80	24.01a
January	39	24.01a
September	96	24.00a
October	90	23.89a

*Means followed by the same letters are not significantly different at the 0.05 % probability level by Duncan's Multiple Range Test.

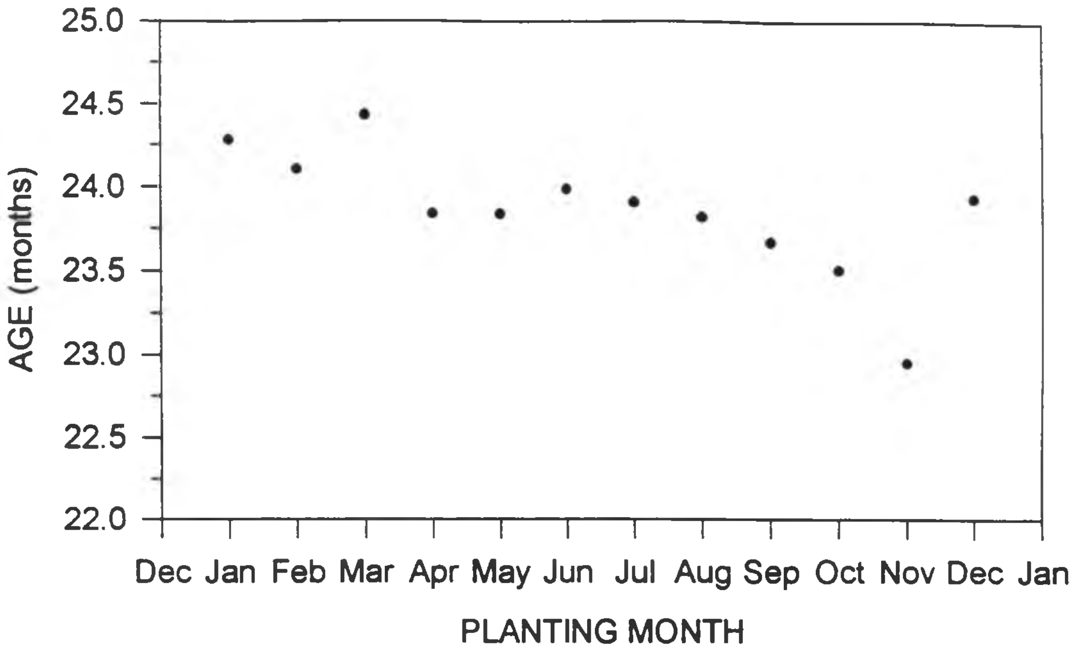


Figure 38. Furrow irrigation mean age at harvest (months) by planting month.

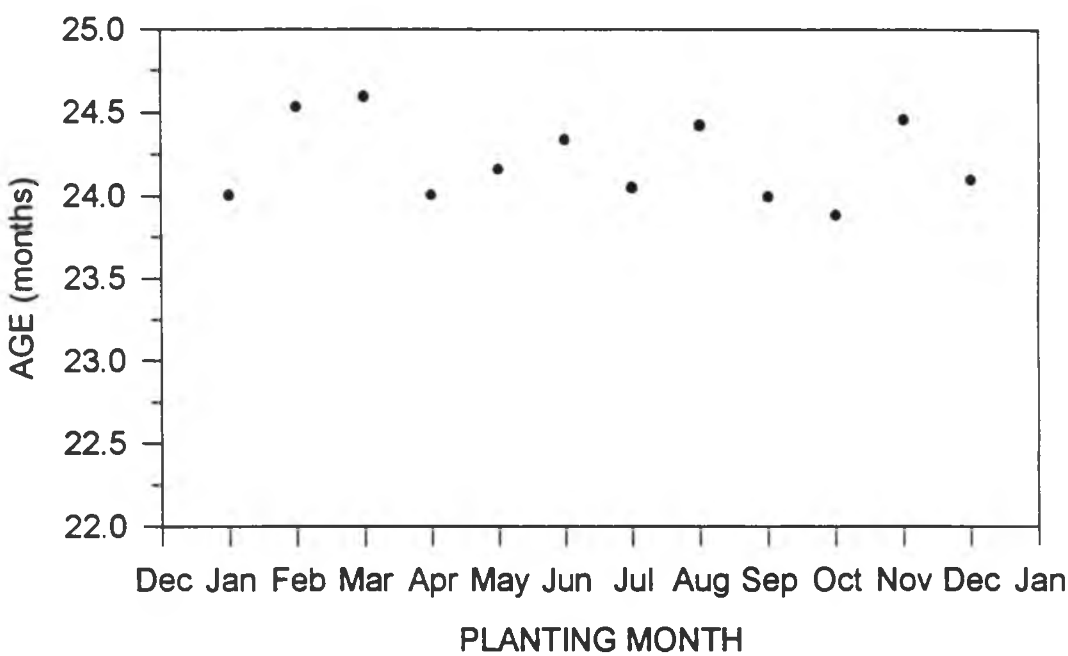


Figure 39. Drip irrigation mean age at harvest (months) by month of planting.

it is not easy to separate the effects, conditions are good for both establishing cane and harvesting cane for good yields. Figure 41 shows a similar relationship between harvest month and planting month using drip irrigation data.

Furrow irrigation mean tonnes sugar hectare^{-1} by harvest (Table 13) is similar to the ranking of means by planting month (Table 8) reflecting the close relationship between time of planting and harvest. The best yields are from cane harvested from January through August. For drip irrigation (Table 14) the best yields are harvested from February to July. There are no harvests in December and only 1 in January.

Canonical variates analysis (results not shown) was used to evaluate how different planting months are based on a set of irrigation and yield variables. Mahalanobis distance indicated that while planting months were different, adjacent months were similar (i.e., March is more like April than it is July). Four planting month groups were created to follow as much as possible the results of the canonical variates analysis (this analysis was done separately from the Duncan's Multiple Range Test described above and is based on a set if water and yield variables rather than one variable) .

November, December and January were not different at the 0.05% level and were classified as group "W". February, March, and April make up start group "A"; May, June, and July start group "B"; and August, September, and October start group "C". These classifications were used for subsequent analyses. The same categories with exception of "W" (little cane is harvested in winter

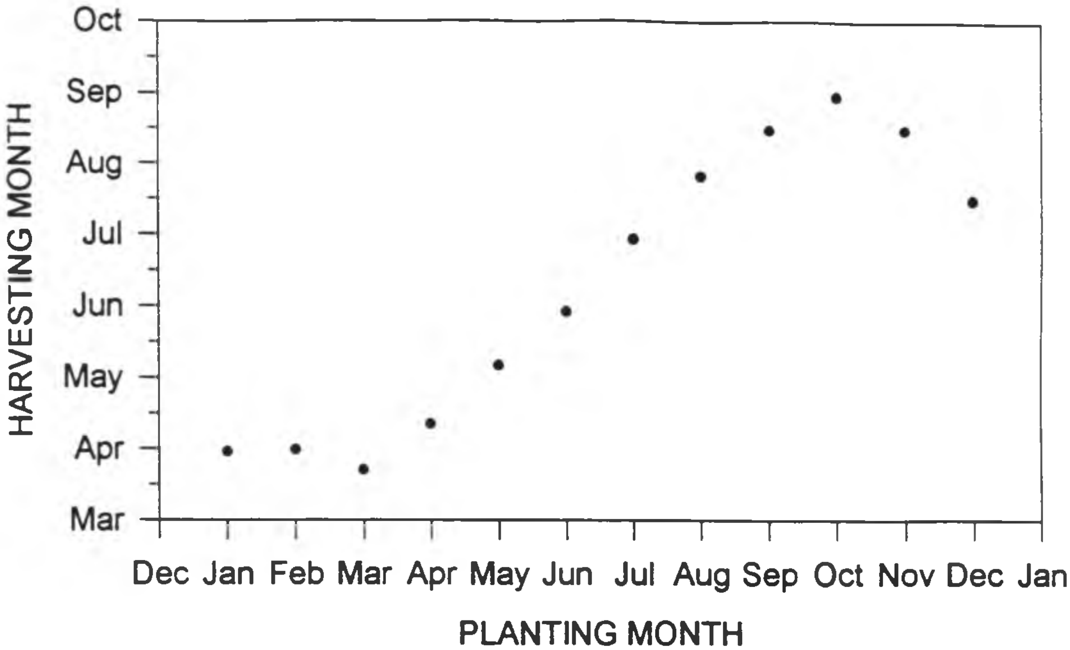


Figure 40. Furrow irrigation mean month of harvest by month of planting. For cane harvested at 24 months of age, the planting month and harvest month is the same.

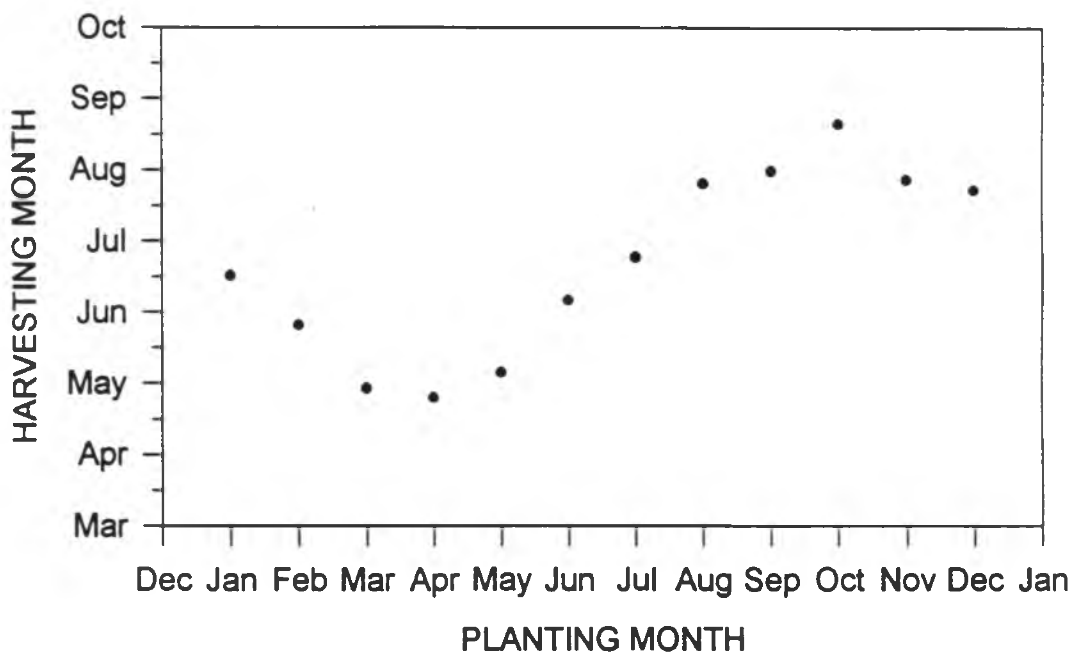


Figure 41. Drip irrigation mean month of harvest by month of planting. For cane harvested at 24 months of age, the planting month and harvest month is the same.

Table 13. Furrow irrigation sugar yield (TSA in Mg ha^{-1}) by month of harvest (HARV).

Harvest Month	n	Yield*
	--harvests--	--Mg ha^{-1}--
May	210	28.44a
June	261	28.24ab
April	193	28.22abc
July	264	27.44abc
March	148	27.31abc
August	293	26.67abc
January	22	26.37abcd
February	73	25.95abcd
September	246	25.64cd
October	201	25.02d
November	20	23.81d
December	3	19.98e

*Means followed by the same letters are not significantly different at the 0.05 % probability level by Duncan's Multiple Range Test.

Table 14. Drip irrigation sugar yield (TSA in Mg ha^{-1}) by month of harvest (HARV).

Harvest Month	n	Yield*
	--harvests--	--Mg ha^{-1}--
April	87	33.32a
May	119	32.51a
June	125	32.23a
March	59	32.14a
February	24	32.03a
July	110	30.84ab
August	129	29.62b
September	105	27.88b
October	103	27.23b
November	27	27.17b
January	1	22.62c
(no December harvests)		

*Means followed by the same letters are not significantly different at the 0.05 % probability level by Duncan's Multiple Range Test.

months) were used as harvest groups. These codes will be used in the following analysis of harvest age and planting month.

To explore whether planting month (start group) and yield relationships change with harvest age, the ranking of mean tonnes sugar $hectare^{-1}$ $month^{-1}$ for drip irrigation by start group was compared for the five harvest age classes first presented in Tables 6 and 7. In Table 15 (harvest age < 22.5 months), the best yields were with startgroup B. The means for startgroups A, W, C were not significantly different at the 0.05% level. Although with only 7 harvests, the best mean tonnes sugar $hectare^{-1}$ $month^{-1}$ is from cane planted from February to April (Table 16 harvest age 22.5-23.5). For cane harvested 23.5 to 24.5 months of age, Table 17, both A and B (February - July) have the best yields.

Winter remains low yielding in Tables 15-17 with harvest ages less than 24.5 months of age. In Table 18, there were only two harvests in startgroup W so it is difficult to evaluate the higher rank. Means overall were less different for this age group. In the younger cane winter (W) is not different that fall (C). In the older cane (Table 19), winter yields are closer to start group B (May to July) as well as group C.

Comparing Drip and Furrow Canonical Correlations

The predrip irrigation database contains the same data for drip and earlier types of irrigation, with the exception of irrigation being in rounds for predrip (furrow) and effective water included as irrigation for drip irrigation. The field history database for drip irrigation has many more variables. The predrip

Table 15. Drip irrigation mean tonnes sugar hectare^{-1} month^{-1} by start group for cane harvested at < 22.5 months of age(code = 1).

Start Group	n	TSAM*
--months--	--harvests--	--Mg ha^{-1}/mo.--
B (May - Jul)	21	1.352a
A (Feb - Apr)	22	1.242b
W (Nov - Jan)	53	1.229b
C (Aug - Oct)	37	1.215b

*Means followed by the same letters are not significantly different at the 0.05 % probability level by Duncan's Multiple Range Test.

Table 16 . Drip irrigation mean tonnes sugar hectare^{-1} month^{-1} by start group for cane harvested at 22.5 - 23.5 months of age (code = 2).

Start Group	n	TSAM*
--months--	--harvests--	--Mg ha^{-1}/mo.--
A (Feb - Apr)	7	1.446a
B (May - Jul)	52	1.344b
C (Aug - Oct)	69	1.195c
W (Nov - Jan)	26	1.178c

*Means followed by the same letters are not significantly different at the 0.05 % probability level by Duncan's Multiple Range Test.

Table 17 . Drip irrigation mean tonnes sugar hectare^{-1} month^{-1} by start group for cane harvested 23.5 - 24.5 months of age (code = 3).

Start Group	n	TSAM*
	--harvests--	--Mg ha^{-1}/mo.--
A (Feb - Apr)	39	1.356a
B (May - Jul)	115	1.341a
C (Aug - Oct)	98	1.218b
W (Nov - Jan)	10	1.180b

*Means followed by the same letters are not significantly different at the 0.05 % probability level by Duncan's Multiple Range Test.

Table 18. Drip irrigation mean tonnes sugar hectare^{-1} month^{-1} by start group for cane harvested at 24.5 - 25.5 months of age (code=4).

Start Group	n	TSAM*
	--harvests--	--Mg/hs/mo.--
A (Feb - Apr)	40	1.364a
W (Nov - Jan)	2	1.358ab
B (May - Jul)	98	1.318ab
C (Aug - Oct)	45	1.178b

*Means followed by the same letters are not significantly different at the 0.05 % probability level by Duncan's Multiple Range Test.

Table 19. Drip irrigation mean tonnes sugar hectare^{-1} month^{-1} by start group for cane harvest at > 25.5 months of age (code =5).

Start Group	n	TSAM*
	--harvests--	--Mg ha^{-1}mo^{-1}--
A (Feb - Apr)	43	1.277a
B (May - Jul)	35	1.247ab
W (Nov - Jan)	50	1.187bc
C (Aug - Oct)	27	1.244c

*Means followed by the same letters are not significantly different at the 0.05 % probability level by Duncan's Multiple Range Test.

irrigation database offered a chance to explore, using canonical correlation to analyze the same variables for both types of irrigation technology. Did relationships between yield and environmental variables (including irrigation) change with change in technology?

Canonical correlation analysis of both the predrip and drip harvests (1950-1994) with nearly the same variables was used to evaluate differences between the two irrigation technologies. Yield variables tonnes cane/hectare (TCA), tonnes sugar hectare^{-1} (TSA), and three juice quality measures (brix, pol, and purity) make up the sets of dependent "yield" variables. The sets of independent "irrigation" variables include irrigation rounds (furrow) or effective water (drip), rain, soil moisture storage (SMS), and elevation. Canonical correlation is similar to the canonical variates analysis described in the previous chapter except that correlations with both yield and irrigation with their own canonical variates and the opposite canonical variates are given.

Cause and effect relations are evaluated with canonical correlation in the same way they are in multiple regression. The results for furrow (predrip) irrigation will be presented first, followed by drip results. A good relationship between irrigation and yield variables is not expected with field history data. There are no variables that give an indication of plant stress during different stages of the crop. In terms of the time, there is overlap between the two technologies. Drip conversion was carried out over a period of years and many mill fields remained furrow.

The furrow irrigation results will be presented in the first five tables, followed by results for drip irrigation. Correlations of yield or irrigation variables with their own canonical variate are likely to be inflated relative to correlations with the opposite canonical variates (Gittins, 1985).

Table 20. Furrow (predrip) canonical correlation eigenvalues, accounted-for variance (%) and F tests for canonical variates (CAN) 1, 2, 3, 4. (Hypothesis tested that canonical correlations in current row all that follow are zero)

CAN	Eigenvalue	Variance (%)	F	Pr>F
1	0.5740	66.79	75.5	0.0001
2	0.2579	30.00	42.84	0.0001
3	0.0262	3.05	8.7	0.0001
4	0.0014	0.17	1.37	0.2531

In Table 20 furrow canonical variates 1 to 3 account for most of the variation. with 66.79% being explained by CAN1. The yield variable (Table 21) with the highest coefficients on the first yield canonical variate (CAN1) is purity. TCA and TSA are highly correlated with yield CAN2 and brix and pol with yield CAN3.

Table 21. Furrow (predrip) canonical structure. Correlations between the yield variables and their canonical variates 1, 2, and 3. Canonical variate 4 was not retained.

Yield Variables	Yield Canonical Variates (CAN)		
	1	2	3
TCA	-0.4068	0.6898	-0.4541
TSA	0.2226	0.8894	-0.3874
BRIX	0.2828	0.4979	0.6264
POL	0.4797	0.5442	0.5689
PUR	0.8561	0.3665	0.0524

TCA = tonnes cane/hectare, TSA = tonnes sugar hectare^{-1}, BRIX = total soluble solids in juice, POL=amount of sugar in juice, Purity = % sucrose in solids.

Table 22 gives the canonical coefficients of the independent set of irrigation variables with their own canonical variates 1, 2, and 3. Elevation has a very high loading on the irrigation canonical variate 1. As elevation may represent temperature as they are strongly correlated. Irrigation has a coefficient of 0.6902 on its own CAN2 and CAN3 is negatively related to rain and soil moisture storage.

Table 23 is a cross loading of yield variables with the irrigation canonical variates. Purity has the highest correlation with irrigation CAN1, TCA and TSA with irrigation CAN2. Table 24 is the cross counterpart with correlation between irrigation variables and yield canonical variates 1, 2, and 3. Elevation is correlated with the first yield canonical variate (CAN1) which is in turn correlated with purity. Irrigation (IRRI) is has a correlation of 0.3125 with yield (CAN2) which in turn is correlated with TCA and TSA.

The same procedure was followed with drip irrigation data (tables 25 -29). The most notable surprise is that soil moisture storage appears to be more important relative to juice quality (table 26 and table 29) than it was with furrow data but was not significant in relation to the second canonical variate for yield (CAN2) which was dominated by TCA (0.9765) and TSA (0.7629)in table 26.

Table 22. Furrow (predrip) canonical structure. Correlations between the irrigation variables and their canonical variates. Canonical variate 4 was not retained.

Irrigation Variables	Irrigation Canonical Variates (CAN)		
	1	2	3
IRRI	-0.4364	0.6902	0.5634
RAIN	-0.1519	0.2144	-0.6016
SMS	0.2317	0.4285	-0.5576
ELEV	0.9007	0.3455	-0.2344

IRRI = irrigation in rounds, RAIN=rainfall total for harvest (mm), SMS = soil moisture storage (mm), ELEV = elevation (m)

Table 23. Furrow (predrip) canonical structure. Correlations between the yield variables and the canonical variates of the irrigation variables. Canonical variate 4 was not retained.

Yield Variables	Irrigation Canonical Variates (CAN)		
	1	2	3
TCA	-0.2456	0.3123	-0.0725
TSA	0.1345	0.4027	-0.0619
BRIX	0.1708	0.2255	0.1001
POL	0.2897	0.2464	0.0909
PUR	0.5170	0.1659	0.0084

TCA = tonnes cane/hectare, TSA = tonnes sugar hectare^{-1}, BRIX = total soluble solids in juice, POL=amount of sugar in juice, Purity = % sucrose in solids.

Table 24. Furrow (predrip) canonical structure. Correlations between the irrigation variables and the canonical variates of the yield variables 1, 2, and 3. Canonical variate 4 was not retained.

Irrigation Variables	Yield Canonical Variates (CAN)		
	1	2	3
IRRI	-0.2636	0.3125	0.0900
RAIN	-0.0917	0.0971	-0.0961
SMS	0.1400	0.1940	0.0891
ELEV	0.5440	0.1564	0.0374

IRRI = irrigation in rounds, RAIN=rainfall total for harvest (mm), SMS = soil moisture storage (mm), ELEV = elevation (m)

Table 25. Drip canonical correlation eigenvalues, accounted-for variance (%) and F tests for canonical variates 1, 2, 3, 4. (Hypothesis tested that canonical correlations in current row all that follow are zero)

CAN	Eigenvalue	Variance (%)	F	Pr>F
1	0.3290	52.82	26.56	0.0001
2	0.1984	31.85	20.96	0.0001
3	0.0935	15.02	13.67	0.0001
4	0.0019	0.31	0.85	0.4277

Table 26. Drip canonical structure. Correlations between the yield variables and their canonical variates. Canonical variate 4 was not retained.

Yield Variables	Yield Canonical Variates (CAN)		
	1	2	3
TCA	0.1302	0.9756	-0.1522
TSA	0..4583	0.7629	0.1601
BRIX	0.5831	-0.5638	-0.0491
POL	0.6689	-0.5638	0.1828
PUR	0.5670	-0.1569	0.6672

TCA = tonnes cane/hectare, TSA = tonnes sugar hectare^{-1}, BRIX = total soluble solids in juice, POL=amount of sugar in juice, Purity = % sucrose in solids.

Table 27. Drip canonical structure. Correlations between the irrigation variables and their canonical variates I1, I2, and I3. Canonical variate 4 was not retained.

Irrigation Variables	Irrigation Canonical Variates (CAN)		
	I1	I2	I3
IRRI	0.2777	0.8953	0.1192
RAIN	-0.7870	0.1628	0.5609
SMS	0.6442	-0.0051	0.6776
ELEV	0.2507	-0.4056	0.6968

IRRI = effective water (mm), RAIN=rainfall total for harvest (mm), SMS = soil moisture storage (mm), ELEV = elevation (m)

Table 28. Drip canonical structure. Correlations between the yield variables and the canonical variates of the irrigation variables. Canonical variate 4 was not retained.

Yield Variables	Irrigation Canonical Variates (CAN)		
	I1	I2	I3
TCA	0.0648	0.3969	-0.0445
TSA	0.2280	0.3104	0.0468
BRIX	0.2901	-0.2294	-0.0144
POL	0.3328	-0.2142	0.0535
PUR	0.2821	-0.0638	0.1951

TCA = tonnes cane/hectare, TSA = tonnes sugar hectare^{-1}, BRIX = total soluble solids in juice, POL=amount of sugar in juice, Purity = % sucrose in solids.

Table 29. Drip canonical structure. Correlations between the irrigation variables and the canonical variates of the yield variables. Canonical variate 4 was not retained.

Irrigation Variables	Yield Canonical Variates (CAN)		
	Y1	Y2	Y3
IRRI	0.1382	0.3643	0.0349
RAIN	-0.3916	0.0662	0.1640
SMS	0.3205	-0.0021	0.1981
ELEV	0.1247	-0.1650	0.2038

IRRI = irrigation in rounds, RAIN=rainfall total for harvest (mm), SMS = soil moisture storage (mm), ELEV = elevation (m)

Spatial Changes in Yield Patterns Following Drip Conversion

Canonical Variates Analysis with Soil Classes

Can yield variables be used to discriminate between different soil groups including soil order, soil series, and soil texture? Canonical variates analysis was used to examine differences between soil classes with the following variables: tonnes sugar hectare^{-1} month^{-1} (TSAM), tonnes cane hectare^{-1} month^{-1} (TCAM), tonnes cane to tonnes sugar (TCTS), pol, and purity. Each analysis was run for both furrow and drip irrigation. The results will be presented in the following order: soil orders, furrow irrigation (Tables 30-33); soil orders, drip irrigation (Tables 34-37); soil series, furrow irrigation (Tables 38-41); soil series, drip irrigation (Tables 42-45).

Yield variables only were chosen for these analyses to explore relations between spatial patterns of yields and soils. Yield patterns may give clues to management of environmental factors influencing yield at the plantation scale. The same variables were used for both drip and furrow. Soils remain the same except for additional fields in two areas added with drip expansion.

The domination of Mollisols can be seen in the soil orders class level information (furrow irrigation) in Table 30 with 67% of the harvests from fields classified as Mollisols. Mill waste fields make up 10.9% of the harvests. Fields classified as Inceptisols are new and are only 0.7% of the harvests. Table 31 lists probabilities that the five yield variables (TSAM, TCAM, TCTS, pol, purity) discriminate between soil orders. Mollisols and Andisols have a probability of 0.048% that they are different, but are very close to being similar at the 0.05% level. All other soil orders and the mill waste field category are different from one another.

The middle column of the first row of data, Table 32, indicates that 92.24% of the variance is explained by the linear combination of the yield variables on the first canonical variate for furrow soil orders. Canonical variates 4 and 5 are not significantly different from zero at the 0.05% level. Table 33 gives the canonical coefficients (called loadings in principal components analysis) for each of the first 4 canonical variates. Canonical variate 1 is dominated by tonnes cane/tonnes sugar (0.9266). Juice quality variables pol and purity are also highly correlated but with

Table 30. Furrow irrigation soil order class level information for canonical variates analysis with 2027 total harvests. (Mill is not a soil order--fields which receive mill waste are grouped together as a class.)

Soil Order	Code	Harvests	Proportion
Andisols	A	61	0.030
Entisols	E	83	0.040
Inceptisols*	I	14	0.007
Mollisols	M	1358	0.670
Oxisols	O	290	0.143
Mill	L	221	0.109

*The Inceptisols (Hailiimaile soil series) were added to the Paia irrigation division shortly before conversion to drip irrigation and fields classified as Ultisols were not added until after drip conversion.

Table 31. Furrow irrigation probability > Mahalanobis distance for squared distance to soil orders . (Mill is not a soil order--fields receiving mill waste are included as a separate category.) A probability of < 0.05% indicates paired groups are different from one another.

From	Andisols	Entisols	Incept.	Mill	Mollisols	Oxisols
Andisols	1.0000	0.0001	0.0001	0.0001	0.0480	0.0062
Entisols	0.0001	1.0000	0.0001	0.0001	0.0001	0.0001
Incept.	0.0001	0.0001	1.0000	0.0001	0.0001	0.0005
Mill	0.0001	0.0001	0.0001	1.0000	0.0001	0.0001
Mollisols	0.0480	0.0001	0.0001	0.0001	1.0000	0.0105
Oxisols	0.0062	0.0001	0.0005	0.0001	0.0105	1.0000

Table 32. Furrow irrigation soil orders eigenvalues, accounted-for variance (%), and F tests for canonical variates (CAN) 1, 2, 3, 4, 5.

CAN	Eigenvalue	Variance (%)	F	Pr>F
1	0.3627	92.24	28.7158	0.0001
2	0.0140	3.56	3.8442	0.0001
3	0.0122	3.10	3.6976	0.0001
4	0.0042	1.08	2.1689	0.0699
5	0.0001	0.01	0.1120	0.7379

Table 33. Furrow irrigation soil order total canonical structure.

	coefficients (loadings) on the canonical variates			
Variable*	CAN1**	CAN2	CAN3	CAN4
TSAM	-0.3694	-0.3148	0.8270	-0.2608
TCAM	0.3403	-0.0876	0.9142	-0.1925
TCTS	0.9266	0.1771	-0.0758	0.2998
POL	-0.6582	-0.0060	-0.0883	-0.3425
PUR	-0.8834	0.1930	0.4017	0.1282

*Variable symbols: TSAM = tonnes sugar hectare^{-1} month^{-1}, TCAM = tonnes cane hectare^{-1} month^{-1}, TCTS = total tonnes cane/total tonnes sugar, POL = pol, PUR = purity

**CAN = canonical variate (CAN5 not retained) the opposite sign. Canonical variate 3 (CAN3) represents yield variability. The coefficient for TCAM on CAN3 is 0.9142 and 0.8270 for TSAM.

The same procedure was repeated for soil orders and drip irrigation yield variables. With drip irrigation, 72.5% of the harvests were from fields classified as Mollisols (Table 34). Mill fields are different from all the soil orders. There were more similarities between soil orders with drip irrigation yield data than with furrow. Mollisols and Andisols are similar and Ultisols and Inceptisols are similar (Table 35). An analysis of soil series for both types or irrigation will be presented in the next section. Soil series is lower in soil classification hierarchy and can be used to further examine where these orders are similar.

Table 36 list accounted for variance for 5 canonical variates of the drip irrigation soil orders. The first canonical variate (CAN1) explains 45.29% of the variance, the second 33.91% and the third 17.33%. The fourth and fifth canonical variates do not explain enough of the variance to be significant. Pol and, inversely, TCTS have the highest coefficients on the first canonical variate (Table 37). Yield variable TSAM has its highest coefficient on the second canonical variate, and purity is highest on the third canonical variate..

For furrow irrigation, ten soil series are represented. Fields receiving mill waste are in a separate category. Table 38 lists the number of harvests since drip conversion for each soils series. Not all fields were converted at the same time so the number harvests reflects the time since conversion as well as the number of fields. The probability matrix in Table 39 indicates similarity between Waiakoa and Alae, Ewa and Molokai, and Paia and Molokai. Ewa and Paia were not similar at the 0.05% level. Most of the variance was accounted for by the first canonical variate (Table 40). The first canonical variate is again dominated by juice quality variables (Table 41). Yield variables TSAM and TCAM have the highest coefficients on CAN2.

Drip irrigation data (Table 42) includes an additional soil series, Hamakuapoko, added with drip expansion, which also increased the number of fields classified as Waiakoa at the opposite end of the plantation. Keahua (23.63%) and Waiakoa (18.45%) soil series have been harvested the most. There are more similarities between soil series with drip irrigation (Table 43). The following are pairs of soil series that were not significantly different at the 0.05% level: Keahua-Alae, Keahua-Waiakoa, Waiakoa-Alae Pulehu-Ewa, Hamakuapoko-Haliimaile, Hamakuapoko-Paia, and Paia-Haliimaile. The similarities appear to relate to location.

The first canonical variate (Table 44) accounts for 49.43% of the variance and seems to be a dominated by sugar variables with a 0.6655 coefficient for TSAM and 0.7473 for pol. TCTS is inversely related to TSAM so it is not surprising that it has an opposite sign. Cane (TCAM) has a coefficient of 0.9573 on CAN2. The similarities in soil series described above are based on yield variable, not soil characteristics.

Table 34. Drip irrigation class level information for 889 observations, 5 variables, and 7 classes (soil orders).

Soil Order	Code	Harvests	Proportion
Andisols	A	31	0.0349
Entisols	E	15	0.0169
Inceptisols	I	41	0.0461
Mollisols	M	645	0.7255
Oxisols	O	111	0.1249
Ultisols*	U	40	0.0450
Mill**	L	6	0.0067

*Fields classified as Ultisols added with drip expansion
**Fields receiving mill waste or water are still primarily furrow irrigated

Table 35. Drip irrigation probability > Mahalanobis distance for squared distance to soil orders. A probability of > 0.05% indicates similarity between groups.

From	Andisols	Entisols	Incept.	Mill*	Moll.	Oxisols	Ultisols
Andisols	1.0000	0.0004	0.0010	0.0015	0.2473	0.0014	0.0001
Entisols	0.0004	1.0000	0.0163	0.0048	0.0001	0.0003	0.0007
Incept.	0.0010	0.0163	1.0000	0.0017	0.0009	0.0145	0.3839
Mill*	0.0015	0.0048	0.0017	1.0000	0.0001	0.0001	0.0024
Moll.	0.2473	0.0001	0.0009	0.0001	1.0000	0.0009	0.0001
Oxisols	0.0014	0.0003	0.0145	0.0001	0.0009	1.0000	0.0004
Ultisols	0.0001	0.0007	0.3839	0.0024	0.0001	0.0004	1.0000

*Mill is not a soil order. Fields receiving mill wastes are assigned a separate category as they receive different management.

Table 36. Drip irrigation soil order eigenvalues, accounted-for variance (%), and F tests for canonical variates 1, 2, 3, 4, 5.

CAN	Eigenvalue	Variance (%)	F	Pr>F
1	0.0655	45.29	4.2047	0.0001
2	0.0490	33.91	3.4532	0.0001
3	0.0251	17.33	2.2951	0.0099
4	0.0036	2.36	0.7367	0.6201
5	0.0015	1.01	0.6432	0.5258

Table 37. Drip irrigation total canonical structure with soil orders. (Canonical variates 5 and 6 not retained.)

	coefficients on the canonical variates (CAN)		
Variable	CAN1	CAN2	CAN3
TSAM	0.4509	0.6931	-0.5164
TCAM	-0.1233	0.4224	-0.6372
TCTS	-0.6904	-0.2008	-0.1148
POL	0.8862	-0.0564	0.3923
PUR	0.4645	0.1865	0.5826

Variable symbols: TSAM = tonnes sugar hectare^{-1} month^{-1}, TCAM = tonnes cane hectare^{-1} month^{-1}, TCTS = total tonnes cane/total tonnes sugar, POL = pol, PUR = purity

Table 38. Furrow irrigation soil series class level information for canonical variates analysis with 2027 total harvests, 5 variables and 10 classes.

Soil Series	Code	Harvests	Proportion
Alae	A	61	0.030
Ewa	E	156	0.077
Haliimaile	H	14	0.007
Jaucas	J	83	0.041
Keahua	K	339	0.167
Mill*	L	221	0.109
Molokai	M	276	0.136
Paia	P	321	0.158
Pulehu	U	277	0.137
Waiakoa	W	279	0.138

*Mill is not a soil series. Fields receiving mill wastes are assigned a separate category as they receive different management .

Table 39. Furrow irrigation probability > Mahalanobis distance for squared distance to soil series. (Mill is not a soil series--fields receiving mill waste are included as a separate category.) A probability of < 0.05% indicates paired groups are different from one another.

From	A	E	H	J	K	Mill	M	P	U	W
A	1.0000	0.0011	0.0001	0.0001	0.0001	0.0001	0.0049	0.0224	0.0016	0.0636
E	0.0011	1.0000	0.0035	0.0001	0.0001	0.0001	0.3804	0.0005	0.0016	0.0001
H	0.0001	0.0035	1.0000	0.0001	0.0001	0.0001	0.0006	0.0001	0.0009	0.0001
J	0.0001	0.0001	0.0001	1.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
K	0.0001	0.0001	0.0001	0.0001	1.0000	0.0001	0.0001	0.0001	0.0001	0.0001
Mill	0.0001	0.0001	0.0001	0.0001	0.0001	1.0000	0.0001	0.0001	0.0001	0.0001
M	0.0049	0.3804	0.0006	0.0001	0.0001	0.0001	1.0000	0.1285	0.0001	0.0001
P	0.0224	0.0005	0.0001	0.0001	0.0001	0.0001	0.1285	1.0000	0.0001	0.0001
U	0.0016	0.0009	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	1.0000	0.0001
W	0.0636	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	1.0000

Soil series: A = Alae, E = Ewa, H = Haliimaile, J = Jaucas, K = Keahua, M = Molokai, P = Paia, U = Pulehu, W = Waiakoa

Table 40. Furrow irrigation soil series eigenvalues, accounted-for variance (%) and F tests for canonical variates (CAN) 1, 2, 3, 4, 5.

CAN	Eigenvalue	Variance (%)	F	Pr>F
1	0.5914	86.57	26.4320	0.0001
2	0.0508	7.43	5.7459	0.0001
3	0.0216	3.17	3.9251	0.0001
4	0.0171	2.50	3.2424	0.0001
5	0.0022	0.33	0.9064	0.4759

Table 41. Furrow irrigation soil series total canonical structure.

	coefficients (loadings) on the canonical variates			
Variable*	CAN1**	CAN2	CAN3	CAN4
TSAM	-0.4017	0.6386	0.4942	-0.4199
TCAM	0.3042	0.6556	0.5920	-0.1954
TCTS	0.8932	0.0534	-0.1602	0.3895
POL	-0.6327	-0.0520	0.2052	-0.2044
PUR	-0.9069	0.1425	0.3532	0.1588

*Variable symbols: TSAM = tonnes sugar hectare^{-1} month^{-1}, TCAM = tonnes cane hectare^{-1} month^{-1}, TCTS = total tonnes cane/total tonnes sugar, POL = pol, PUR = purity

**CAN = canonical variate (CAN5 not retained)

Table 42. Drip irrigation soil series information for canonical variates analysis with 889 total harvests, 5 variables and 11 classes.

Soil Series	Code	Harvests	Proportion
Alae	A	311	3.48
Ewa	E	54	6.07
Haliimaile	H	41	4.61
Jaucas	J	15	1.68
Keahua	K	210	23.62
Mill*	L	6	0.67
Molokai	M	104	11.69
Hamakuapoko**	O	40	4.50
Paia	P	139	15.63
Pulehu	U	85	9.55
Waiakoa	W	164	18.45

*Mill is not a soil series. Fields receiving mill wastes are assigned a separate category. Most mill fields are still furrow irrigated so the number of drip mill harvests is very low.

**Fields classified as Hamakuapoko soil series added as part of drip expansion

Table 43. Drip irrigation probability > Mahalanobis distance for squared distance to soil series. (A probability of < 0.05% indicates paired groups are different from one another.)

From	A	E	H	J	K	M	O	P	U	W
A	1.0000	0.0850	0.0005	0.0002	0.1471	0.0007	0.0001	0.0001	0.0003	0.7458
E	0.0850	1.0000	0.0002	0.0004	0.0001	0.0107	0.0001	0.0001	0.1867	0.0029
H	0.0005	0.0002	1.0000	0.0139	0.0001	0.0109	0.3323	0.0738	0.0001	0.0001
J	0.0002	0.0004	0.0139	1.0000	0.0001	0.0002	0.0004	0.0002	0.0098	0.0001
K	0.1471	0.0001	0.0001	0.0001	1.0000	0.0001	0.0001	0.0001	0.0001	0.0533
M	0.0008	0.0107	0.0109	0.0002	0.0001	1.0000	0.0002	0.0001	0.0004	0.0001
O	0.0007	0.0001	0.3323	0.0004	0.0001	0.0002	1.0000	0.6834	0.0001	0.0001
P	0.0001	0.0001	0.0738	0.0002	0.0001	0.0001	0.6834	1.0000	0.0001	0.0001
U	0.0003	0.1867	0.0001	0.0098	0.0001	0.0004	0.0001	0.0001	1.0000	0.0001
W	0.7458	0.0029	0.0001	0.0001	0.0533	0.0001	0.0001	0.0001	0.0001	1.0000

Soil series: A = Alae, E = Ewa, H = Haliimaile, J = Jaucas, K = Keahua, M = Molokai, O = Hamakuapoko P = Paia, U = Pulehu, W = Waiakoa, (Mill omitted)

Table 44. Drip irrigation soil series eigenvalues, accounted-for variance (%) and F tests for canonical variates (CAN) 1, 2, 3, 4, 5. (The null hypothesis is that canonical correlations in current row all that follow are zero)

CAN	Eigenvalue	Variance (%)	F	Pr>F
1	0.1949	49.53	6.6997	0.0001
2	0.1271	32.31	4.7302	0.0001
3	0.0550	13.98	2.5845	0.0001
4	0.0097	2.47	1.0305	0.4191
5	0.0067	1.71	0.9861	0.4333

Table 45. Drip irrigation total canonical structure with soil series. (Canonical variates 5 and 6 not retained.)

	coefficients on the canonical variates (CAN)		
Variable	CAN1	CAN2	CAN3
TSAM	0.6655	0.6290	0.3999
TCAM	0.1429	0.9573	0.0102
TCTS	-0.6439	0.4653	-0.3746
POL	0.7473	-0.6016	0.1509
PUR	0.3794	-0.3187	0.3640

Variable symbols: TSAM = tonnes sugar hectare^{-1} month^{-1}, TCAM = tonnes cane/hectare/month, TCTS = total tonnes cane/total tonnes sugar, POL = pol, PUR = purity

Analysis of Spatial Groups Defined by Pan Assignments

Field history data used for much of the spatial analysis consists of means by fields and means for each of the 157 sugarcane fields which cover 14,600 hectares of land (Fig. 42). The fields numbers in the 100's are all located in the northernmost section of plantation. Fields numbered in the 200's, 300's, and 400's are along the eastern side of the plantation, and the 500's and 800's are in the center. The low elevations along the western side of the plantation through the narrowest section of island are occupied by fields in the 600's, 700's and 900's. Potential evaporation estimates from evaporation pans, later replaced with calculations from automatic station data (modified Penman), are assigned to groups of fields which closely coincide with areas defined by field numbering (Fig. 43).

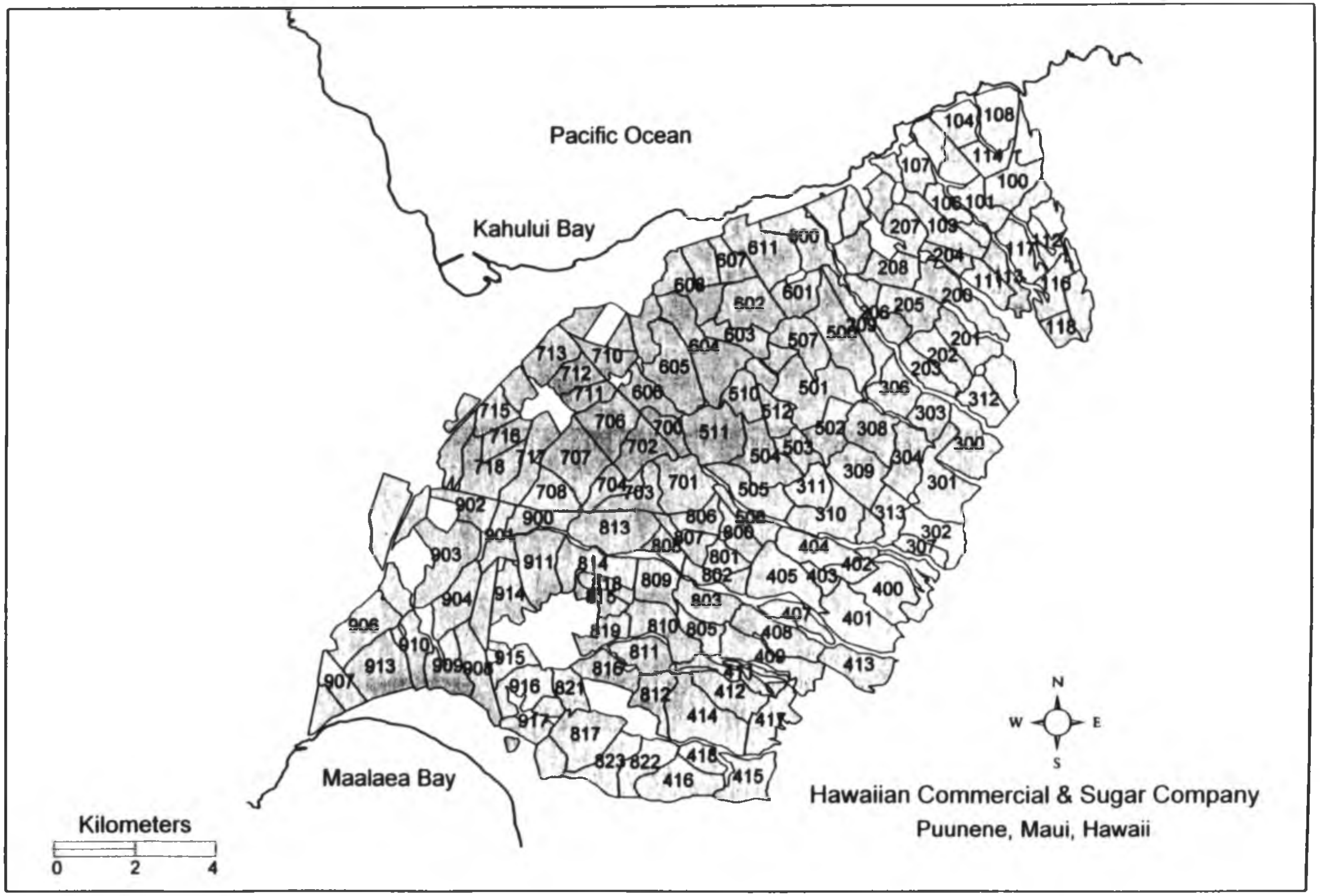


Figure 42. Map of HC&S fields showing field numbering pattern.

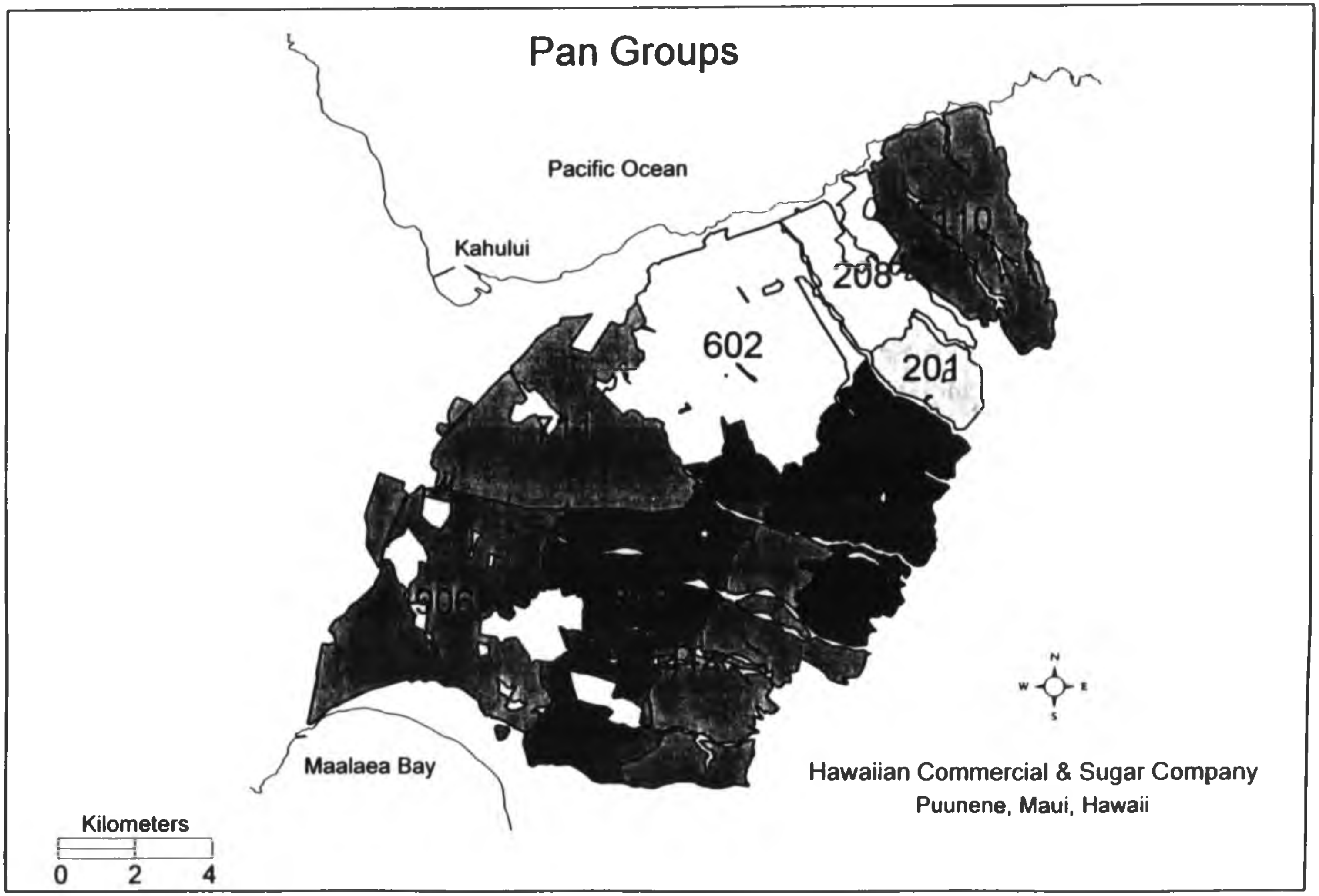


Figure 43. Fields assigned the same evaporation values mapped as areas (pan groups).

Fields numbered in the 100's make up pan groups 107 (208) and 110. Fields at the highest elevations are included in pan groups 110, 201, 301, 414 (Fig. 44)..

Furrow irrigation tonnes sugar hectare^{-1} (TSA in Mg ha^{-1}) means by pan groups are significantly different. Keahua Division (pan groups 301 and 414) have the highest yields (Table 46). Mean TSAM for furrow irrigation is also much higher for pan groups 301 and 414 (Fig. 45). With drip irrigation, mean tonnes sugar hectare^{-1} increased for all the pan groups (Table 47). Their relative ranking within the plantation also changed with the change from furrow irrigation to drip. The highest mean tonnes sugar hectare^{-1} is for pan group 906 (Maalaea Division). These fields have the highest water demand and did not become high yielding until after the conversion to drip irrigation (Table 25). Also high yielding with drip irrigation are pan groups 602 and 711. Even though pan groups 110 and 201 were assigned the same data from 1989-1994 , pan group 201 is at a higher elevation and the planting dates and harvest age may have been different.

The increase in yield (TSAM) from the wet (110) to dry (906) with drip irrigation is in striking contrast to the spatial pattern indicated in Fig. 45 for furrow irrigation (Fig. 46) .

Furrow tonnes cane ha^{-1} production is highest in pan groups 711 and 110 (Table 48). Mill fields have high cane production because of the nutrients applied, but have low sugar yields. Drip cane production (tonnes cane/ha) is highest in pan group 906 and lowest in pan group 414 (Table 49).

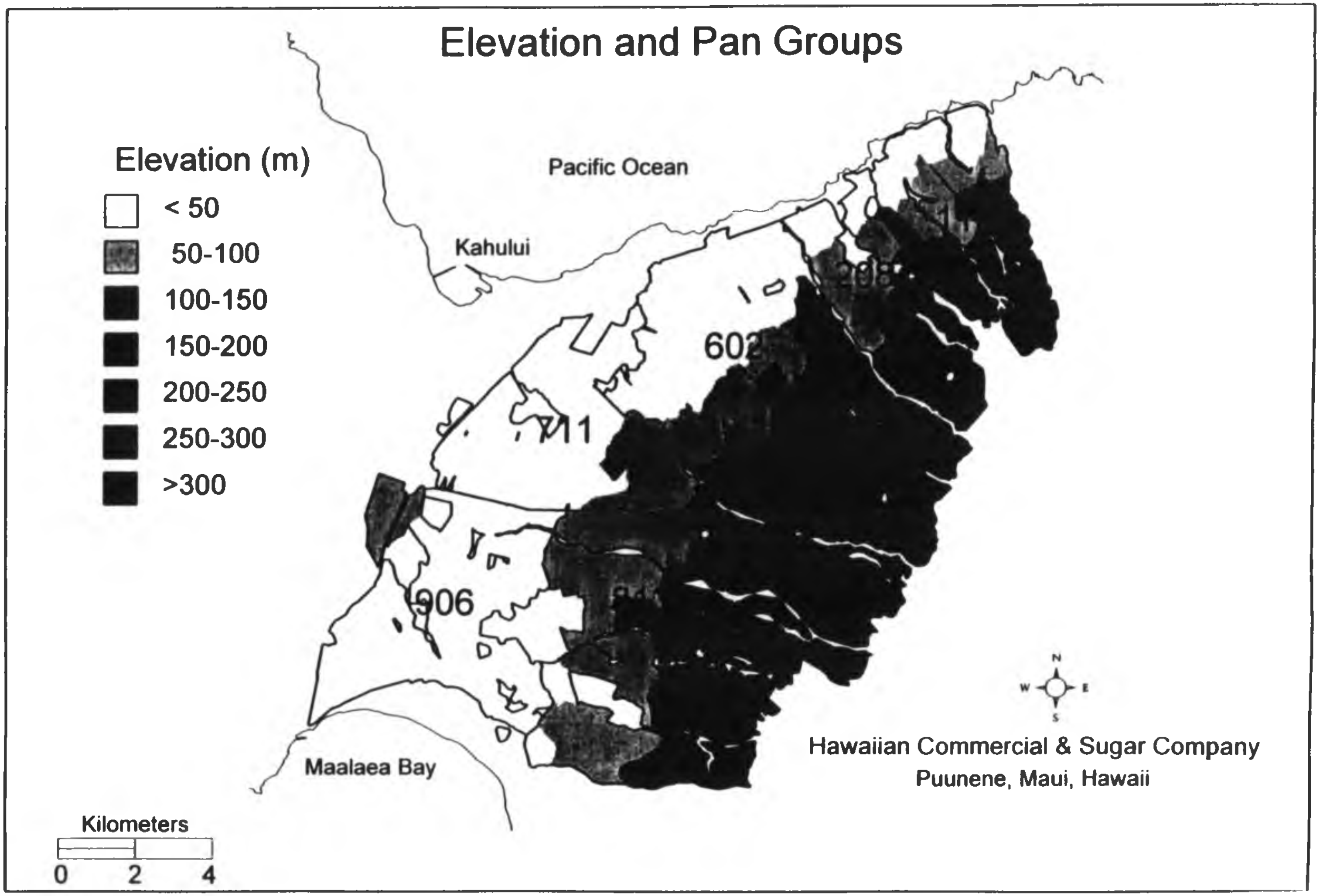


Figure 44. Map of evaporation (pan) groups and elevation (m).

Table 46. Furrow irrigation mean sugar yield (TSA in Mg ha^{-1}) by pan group (fields assigned the same potential evapotranspiration value) .

Pan Group	n	Yield*
	--harvests--	--Mg ha^{-1}--
301	223	29.32a
414	107	28.83a
201	43	28.61a
602	301	27.44b
813	368	26.69bc
110	125	26.65bc
711	325	26.38c
107	181	26.17c
906	233	25.65c

*Means followed by the same letters are not significantly different at the 0.05 % probability level by Duncan's Multiple Range Test.

Table 47. Drip irrigation mean sugar yield (TSA in Mg ha^{-1}) for groups of fields with the same assigned potential evapotranspiration (pan group). The number of harvests within each pan group is indicated by n.

Pan Group	n	Yield*
	--harvests--	--Mg ha^{-1}--
906	68	32.41a
711	62	31.80ab
602	115	31.79ab
301	130	31.61bc
813	184	30.80abc
201	31	30.45bcd
414	97	30.17cd
107	60	29.50d
110	136	27.67e

Note: 110 and 201 had identical data from 1989-1994
*Means followed by the same letters are not significantly different at the 0.05 % probability level by Duncan's Multiple Range Test.

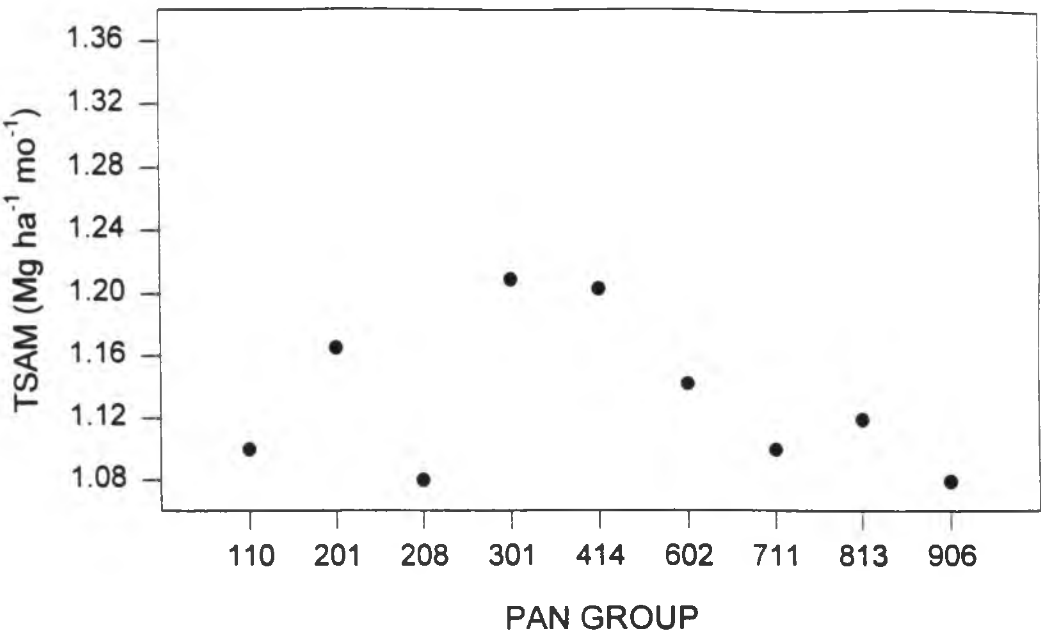


Figure 45. Furrow irrigation mean TSAM in tonnes sugar hectare^{-1} month^{-1} by pan group. Fields within each pan group are assigned the same evaporation values.

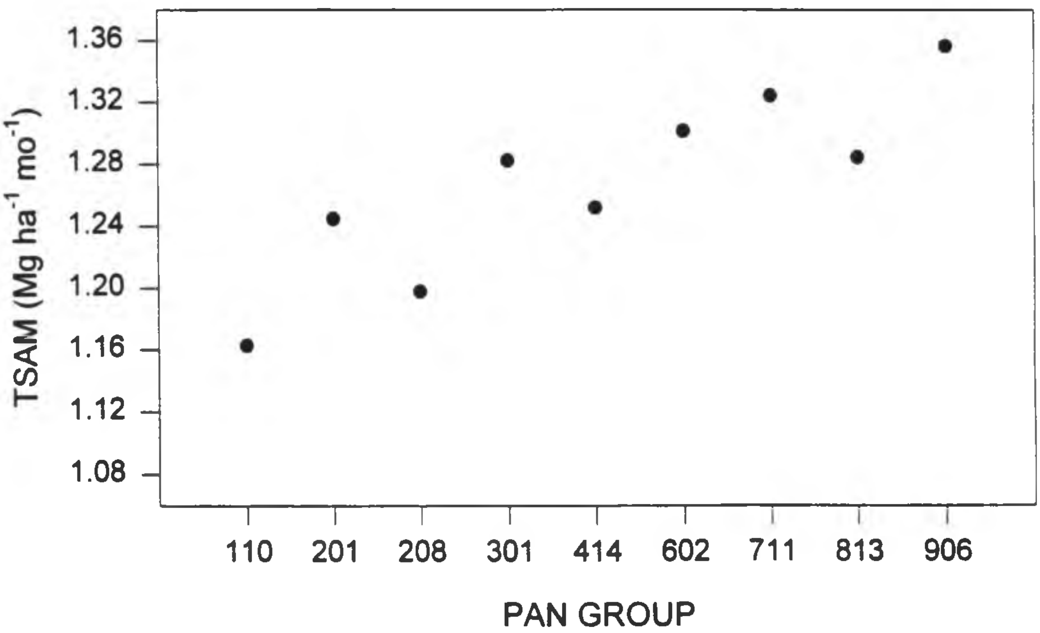


Figure 46. Drip irrigation mean TSAM in tonnes sugar hectare^{-1} month^{-1} by pan group. Fields within each pan group are assigned the same evaporation values.

Table 48. Furrow irrigation mean cane yield (TCA in Mg ha^{-1}) by pan group (fields assigned the same potential evaporation value).

Pan Group	n	Yield*
	--harvests--	--Mg ha^{-1}--
711	325	221.88a
110	125	218.66ab
906	233	218.02ab
602	301	217.37abc
107	181	216.94abc
301	223	214.12bcd
201	43	212.07bcd
414	107	210.02cd
813	368	209.04d

*Means followed by the same letters are not significantly different at the 0.05 % probability level by Duncan's Multiple Range Test.

Table 49. Drip irrigation mean cane yield (TCA) for groups of fields with the same potential evaporation assigned. The number of harvests within each pan group is indicated by n.

Pan Group	n	Yield*
	--harvests--	--Mg ha^{-1}--
906	68	249.3a
711	62	233.9b
602	115	232.4b
107	60	225.4bc
813	184	223.7bcd
301	130	222.7bcd
201	31	221.8bcd
110	136	217.5cd
414	97	211.2d

Note: 110 and 201 had identical data from 1989-1994
*Means followed by the same letters are not significantly different at the 0.05 % probability level by Duncan's Multiple Range Test.

In Table 50, Keahua Division received the least irrigation (furrow) but had the highest yields (and SMS). Pan groups numbers are not properly indicated on the x-axis in Fig. 47. The data label is the first number in the pan group field identifier. Note the low irrigation for pan groups 301 and 414 and the high amounts given pan 906. Figure 48 is a graph of mean rainfall (furrow) by pan group clearly indicating that rainfall decreases as field number increases.

Keahua Division pan groups 301 and 414 received relatively more water with drip but 906 has the highest yields (Table 51). Fig. 49 shows the pattern of gross water applied by pan group and Fig. 50 shows PE per month by pan group. PE values in Table 52 are accumulated over the entire crop cycle and vary with planting date. Pan groups 301 and 414 have high PE which explains their relative standing with gross water applied. Gross water applied is strongly correlated with PE (except when just established and during ripening), in contrast to the inverse relationship between irrigation rounds (furrow) and soil moisture storage. PE was divided by age in months (PEM) in Fig. 50 to reduce the influence of age. In Fig. 50 pan group 301 is second to 906 in PE mm mo^{-1}.

In the following section, the location of soil orders and soil series relative the pan groups (areas of fields assigned the same potential evapotranspiration values) will be discussed. Because climate and soils are interrelated separating the two effects is not always simple. Sugarcane in the field responds to actual evaporation. How well the plantation can replace the water used in actual evaporation depends on the accuracy of the potential evaporation estimates. Pan

Table 50. Furrow irrigation rounds (IRRI) for two-year harvest cycle by pan group (fields assigned the same potential evaporation value).

Pan Group	n	Irrigation*
	--harvests--	--mm--
906	233	40.6a
711	325	38.1b
813	368	37.6bc
110	125	37.1bc
107	181	36.3c
602	301	36.2c
201	43	33.6d
301	223	33.3d
414	107	33.0d

*Means followed by the same letters are not significantly different at the 0.05 % probability level by Duncan's Multiple Range Test.

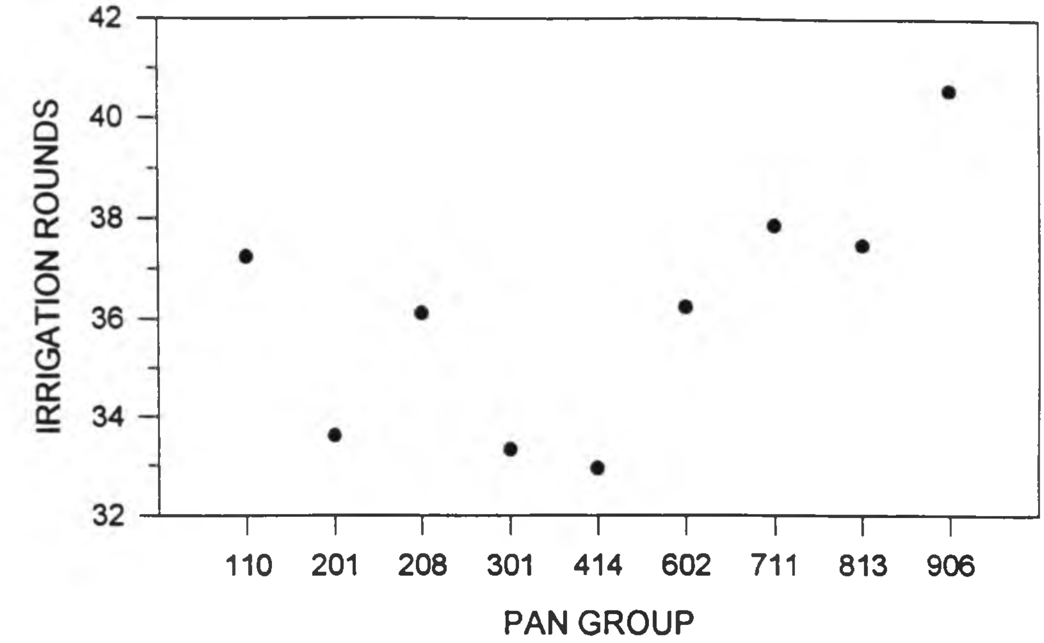


Figure 47. Furrow irrigation rounds by pan group. Fields within each pan group are assigned the same evaporation values.

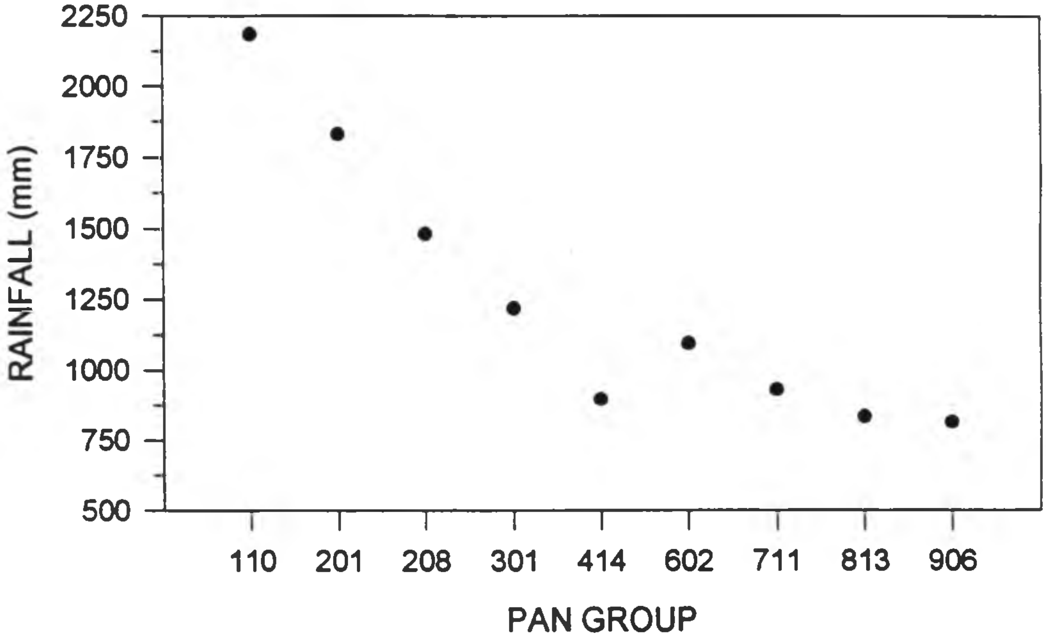


Figure 48. Furrow irrigation mean rainfall (mm) by pan group. Fields within each pan group are assigned the same evaporation values.

Table 51. Drip irrigation mean gross water applied (GW_APPL) for the entire crop cycle by pan group.

Pan Group	n	Irrigation*
	--harvests--	--mm--
906	68	4913.3a
414	97	4467.1b
301	130	4433.7b
711	62	4245.8bc
813	184	4245.3bc
602	115	4169.1c
107	60	3859.9d
201	31	3614.3e
110	136	2929.1f

Note: 110 and 201 had identical data from 1989-1994
*Means followed by the same letters are not significantly different at the 0.05 % probability level by Duncan's Multiple Range Test.

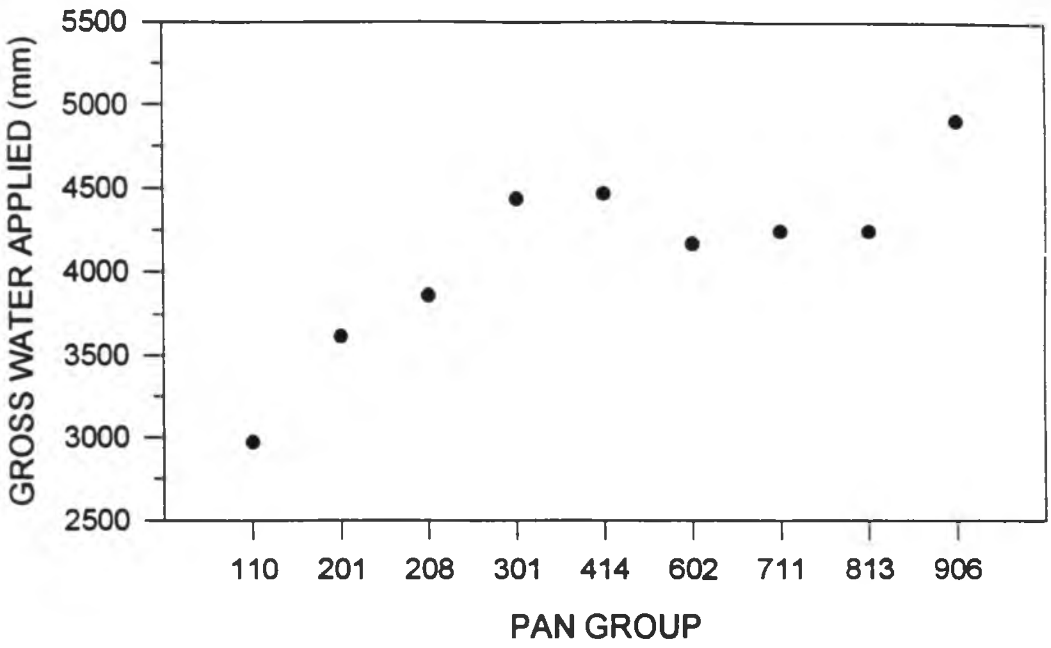


Figure 49. Drip irrigation gross water applied (mm) by pan group. Fields within each pan group are assigned the same evaporation values.

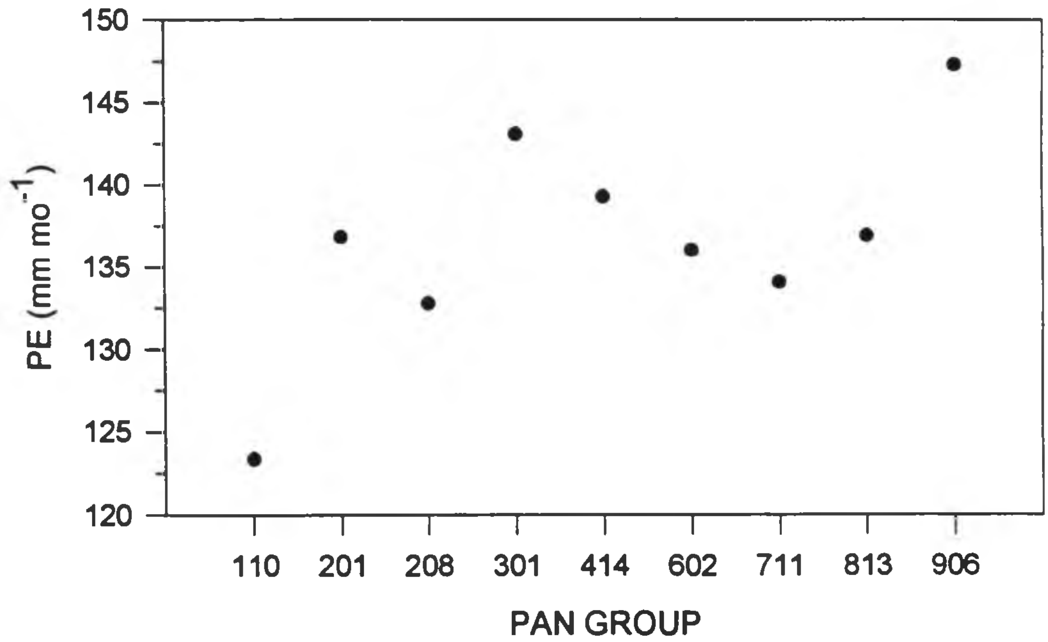


Figure 50. Drip irrigation potential evapotranspiration (mm) per month by pan group. Fields within each pan group are assigned the same evaporation values.

Table 52. Drip irrigation mean potential evapotranspiration (PE) for the entire crop cycle (not location) by pan group. The PE values reflect age and planting date.

Pan Group	n	PE*
	--harvests--	--mm--
301	130	3532.5a
906	68	3511.2a
414	97	3363.5ab
201	31	3361.4ab
602	115	3332.0bc
813	184	3284.2bc
107	60	3277.0bc
711	62	3179.0c
110	136	2942.6d

Note: 110 and 201 had identical data from 1989-1994
*Means followed by the same letters are not significantly different at the 0.05 % probability level by Duncan's Multiple Range Test.

groups reflect the scale at which PE values are assigned. The pan groups represent a management spatial pattern, not a natural one.

Spatial Overlap of Soil and Pan Groups

Fields receiving mill waste are listed as a separate category as the mill waste treatment overshadows differences in soil (Table 53). Most of these fields are still furrow irrigated. The classification is not included under drip. Fields dominated by the soil order Inceptisols are shown with only 14 harvests, indicating the area is likely to have been part of the expansion into pineapple land. As with drip irrigation, the majority of the harvests are from fields classified as Oxisols and Mollisols and are high yielding. Notably different from drip irrigation is the low ranking (furrow) of the soil order Entisols represented by fields dominated with Jaucas sand along the saddle of Maui.

As indicated by the large number of harvests in Table 54 since drip conversion (642), most of the fields at HC&S are dominated by soils belonging to the soil order Mollisols. The highest yield in tonnes sugar hectare^{-1} for a soil order is seen with Oxisols (Molokai soil series). The letters indicate that these yields are not significantly different than the other soils orders, except for the soil order Ultisols (Hamakuapoko). These soil series are located a region of the plantation where there is higher rainfall. Alae is the only soil series at the plantation belonging to the soil order Andisols (Fig. 51).

Both Jaucas and Puuone soil series of the soil order Entisols (Fig. 52) are found at the plantation. Jaucas covers enough area to be counted at field level

Table 53. Furrow irrigation mean sugar yields (TSA in Mg ha^{-1}) by soil order (mill waste fields are a separate category).

Soil Order	n	Yield*
	--harvests--	--Mg ha^{-1}--
Inceptisols	14	29.62a
Oxisols	286	27.72b
Mollisols	1342	27.18bc
Andisols	59	25.89cd
Entisols	73	25.28d
Mill	197	24.87d

*Means followed by the same letters are not significantly different at the 0.05 % probability level by Duncan's Multiple Range Test.

Table 54. Drip irrigation mean sugar yields (TSA in Mg ha^{-1}) by soil order for (mill water fields are a separate category).

Soil Order	n	Yield*
	--harvest--	--Mg ha^{-1}--
Oxisols	109	32.17a
Entisols	14	31.45a
Mollisols	642	30.63ab
Inceptisols	41	30.11ab
Andisols	31	29.48ab
Ultisols	40	28.02b

*Means followed by the same letters are not significantly different at the 0.05 % probability level by Duncan's Multiple Range Test.

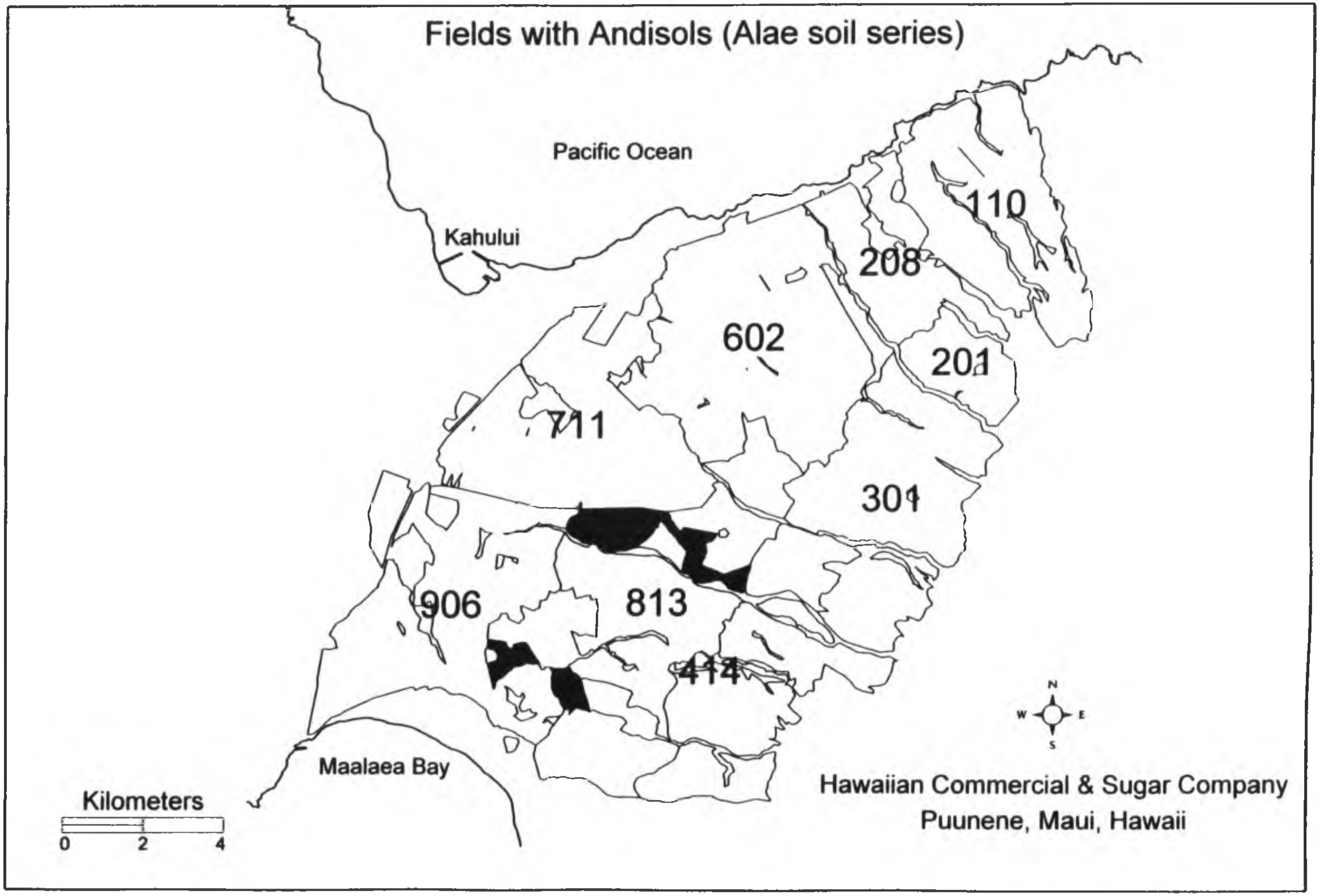


Figure 51. Map of fields with Andisols (Alae soil series).

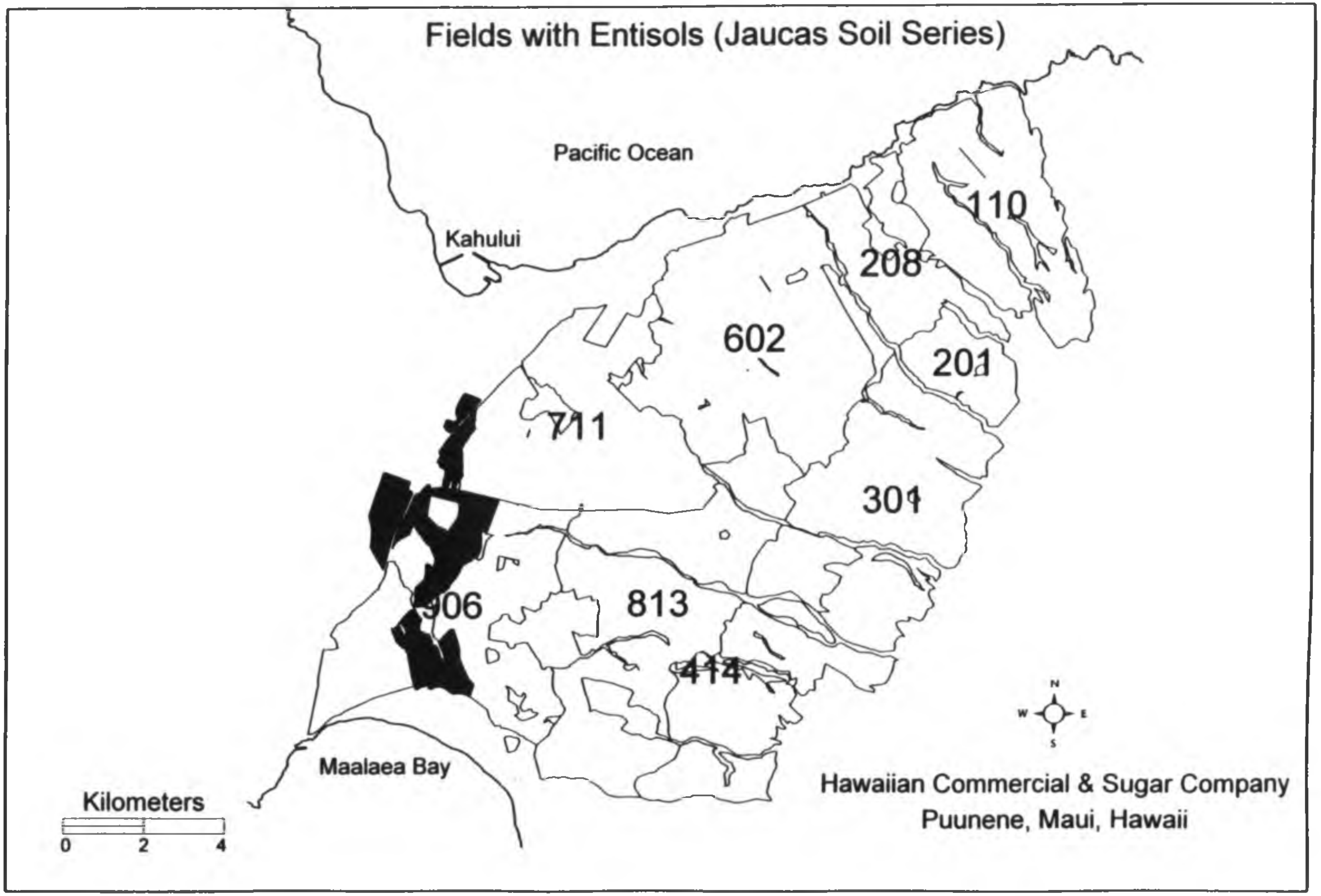


Figure 52. Map of fields with Entisols (Jaucas soil series).

while Puuone does not. The Inceptisols (Haliimaile soil series) are located at the most windward and wettest end of the plantation in pan groups 110 and 201 (Fig. 53).

The dominant soils of the plantation are Mollisols represented by the soil series Ewa, Keahua, Paia, Pulehu and Waiakoa. Keahua soil series is found at the higher elevation in pan groups 301 and 414 (Fig. 54). These soils have been used for growing sugarcane for hundreds of harvests. Pulehu is found in the most rain shadowed areas of the plantation along with the Ewa soil series. Paia soil series is located along in the most windward part of the plantation with more cloudiness and rainfall. Waiakoa is located in center and lower edge of the plantation.

Molokai soil series (Oxisols) defines an area so close to that of pan group 602 that it is not possible to sort out the spatial effects of soil and climate (Fig. 55). In Fig. 56, Hamakuapoko soil series (Ultisols) dominates fields acquired with the expansion of the plantation following the conversion to drip irrigation (upslope of Paia soils in pan group 110).

Rainfall is cumulative over the entire two-year crop cycle thus reflecting the planting date and age of the crop as well as actual rainfall (Table 55). The Inceptisols (Hailiimaile soil series), only 14 harvests, have the highest mean rainfall and the highest mean tonnes sugar hectare^{-1} (Table 7). The soil orders Entisols and Andisols had the lowest mean rainfall. The mill fields near Paia mill and those near Puunene are shown as one region. If considered separately, the Paia mill waste fields have more rainfall.

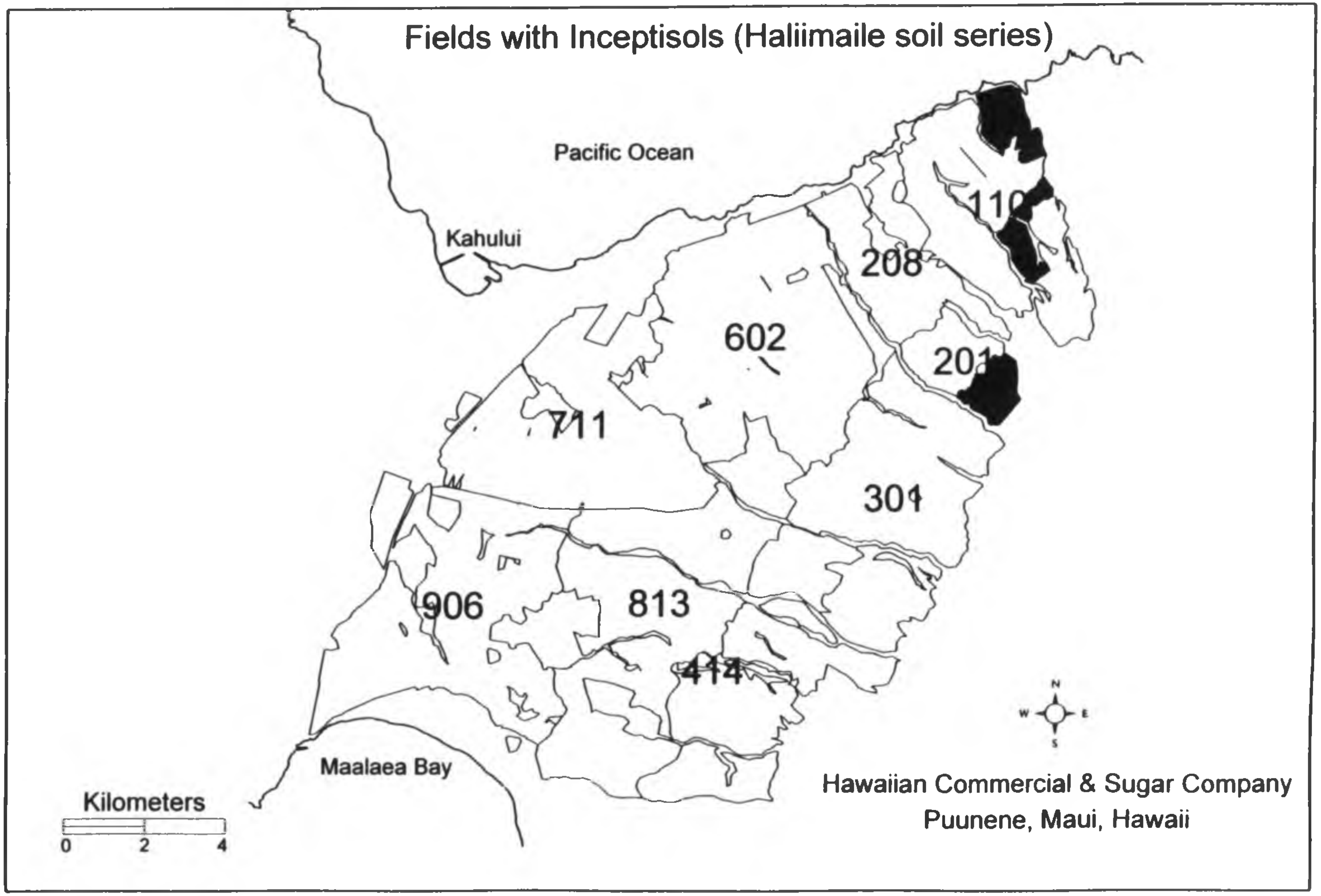


Figure 53. Map of fields with Inceptisols (Haliimaile soil series).

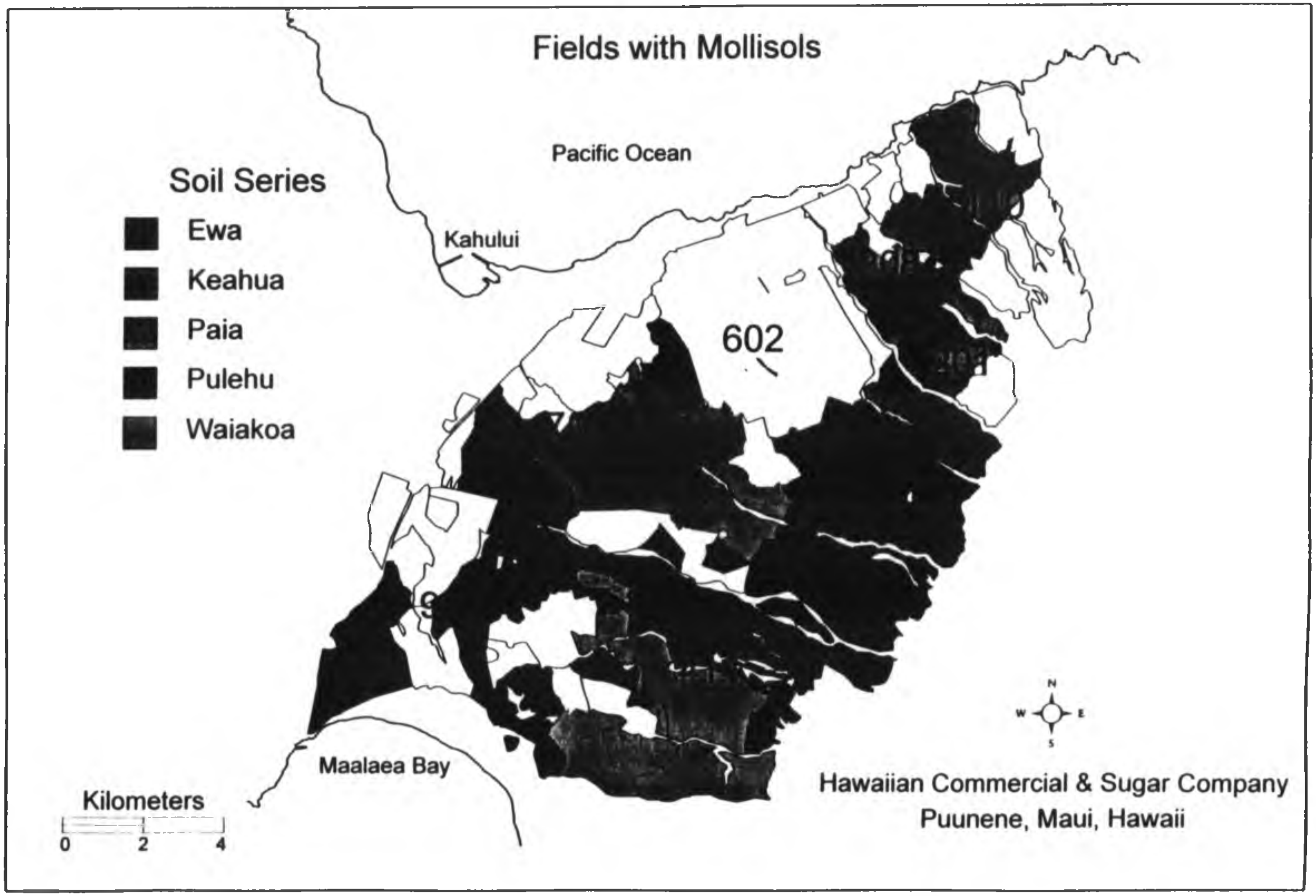


Figure 54. Map of fields with Mollisols including soil series Ewa, Keahua, Paia, Pulehu, and Waiakoa.

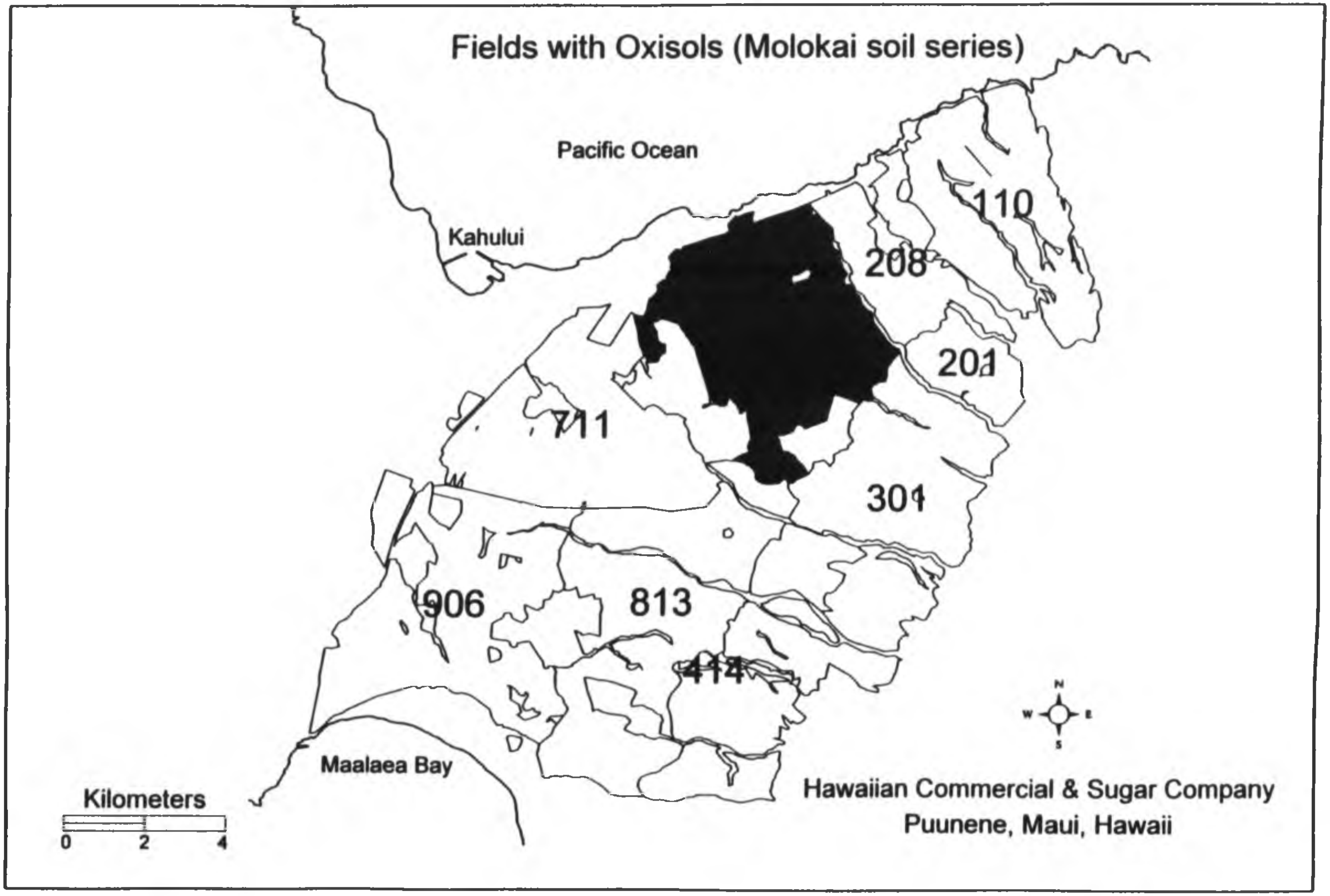


Figure 55. Map of fields with Oxisols (Molokai soil series).

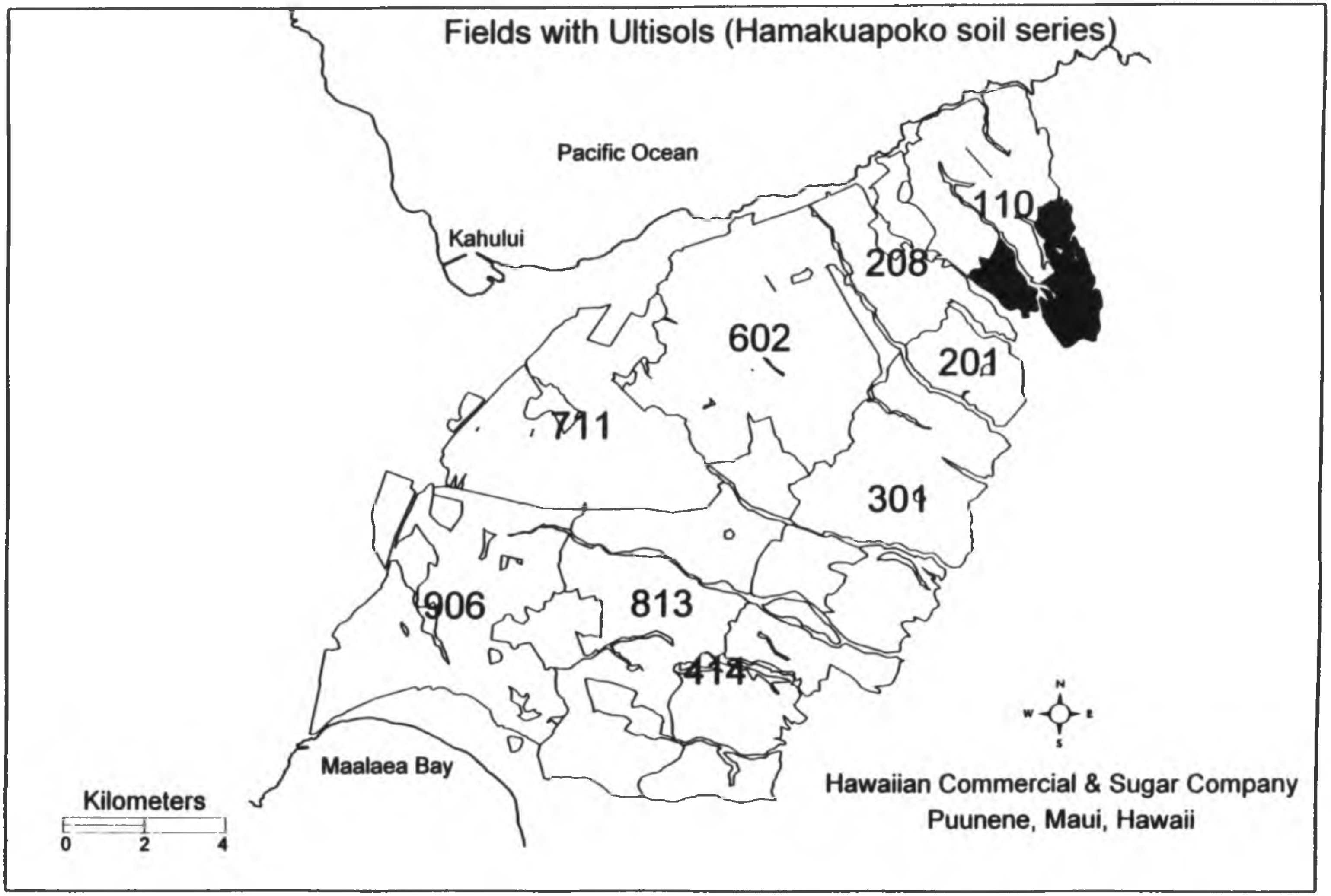


Figure 56. Map of fields with Ultisols (Hamakuapoko soil series).

Table 55. Furrow irrigation mean rainfall (RAIN) for the two-year crop cycle by soil order (mill waste fields are included as a category).

Soil Order	n	Rain*
	--harvests--	--mm--
Inceptisols	14	2068.4a
Mill	197	1200.9b
Oxisols	286	1150.6b
Mollisols	1342	1138.1b
Entisols	73	862.5c
Andisols	59	805.1c

*Means followed by the same letters are not significantly different at the 0.05 % probability level by Duncan's Multiple Range Test.

The seven fields classified as Hamakuapoko soil series have a mean elevation of 228 meters and the twenty-seven fields classified Keahua soil series have a mean elevation of 200 meters (Table 56). The eleven mill fields have the lowest mean elevation, 21 meters.

The Keahua soils series area (shown earlier as on of the Mollisol soil series) look homogeneous only when the major soil type is mapped at the field scale (Figure 57). When mapped by map unit (SCS soil survey), it can be shown to be comprised of 5 soil types. (Loss of specific soil information in favor of more general information at field level or above is necessary when evaluating for large areas and evaluating soils at the same scale as other data for the entire plantation.)

Fields dominated by soils classified as Haliimaile soil series were converted to sugarcane shortly before drip conversion had very high yields for the first harvests (Table 57). The largest group of harvests (338) were from field classified as Keahua soil series. These fields were consistently the highest yielding with furrow irrigation and were closely followed in productivity by Molokai soil series. The lowest yielding fields belonged to soil series Pulehu, Waiakoa, Alae, and Jaucas all of which are located in the rain-shadowed area of the plantation having the highest potential evapotranspiration. Mill fields were not significantly different from this group.

The soil series with the highest tonnes sugar hectare^{-1} with drip irrigation were Pulehu, Ewa, Molokai, Keahua, Waiakoa, and Haliimaile (Table 58). The

Table 56. Mean elevation (ELEV) of fields by soil series. (Note: n = the number of fields in each soil series not harvests.)

Soil Series	n	Elevation*
	--fields--	--mm--
Hamakuapoko	7	228.3a
Keahua	27	200.0ab
Haliimaile	6	174.0b
Paia	22	125.3c
Waiakoa	25	92.2cd
Alae	5	68.2de
Molokai	18	57.9de
Ewa	11	48.6de
Jaucas	8	41.9e
Pulehu	18	39.6e
Mill	11	21.4e

*Means followed by the same letters are not significantly different at the 0.05 % probability level by Duncan's Multiple Range Test.

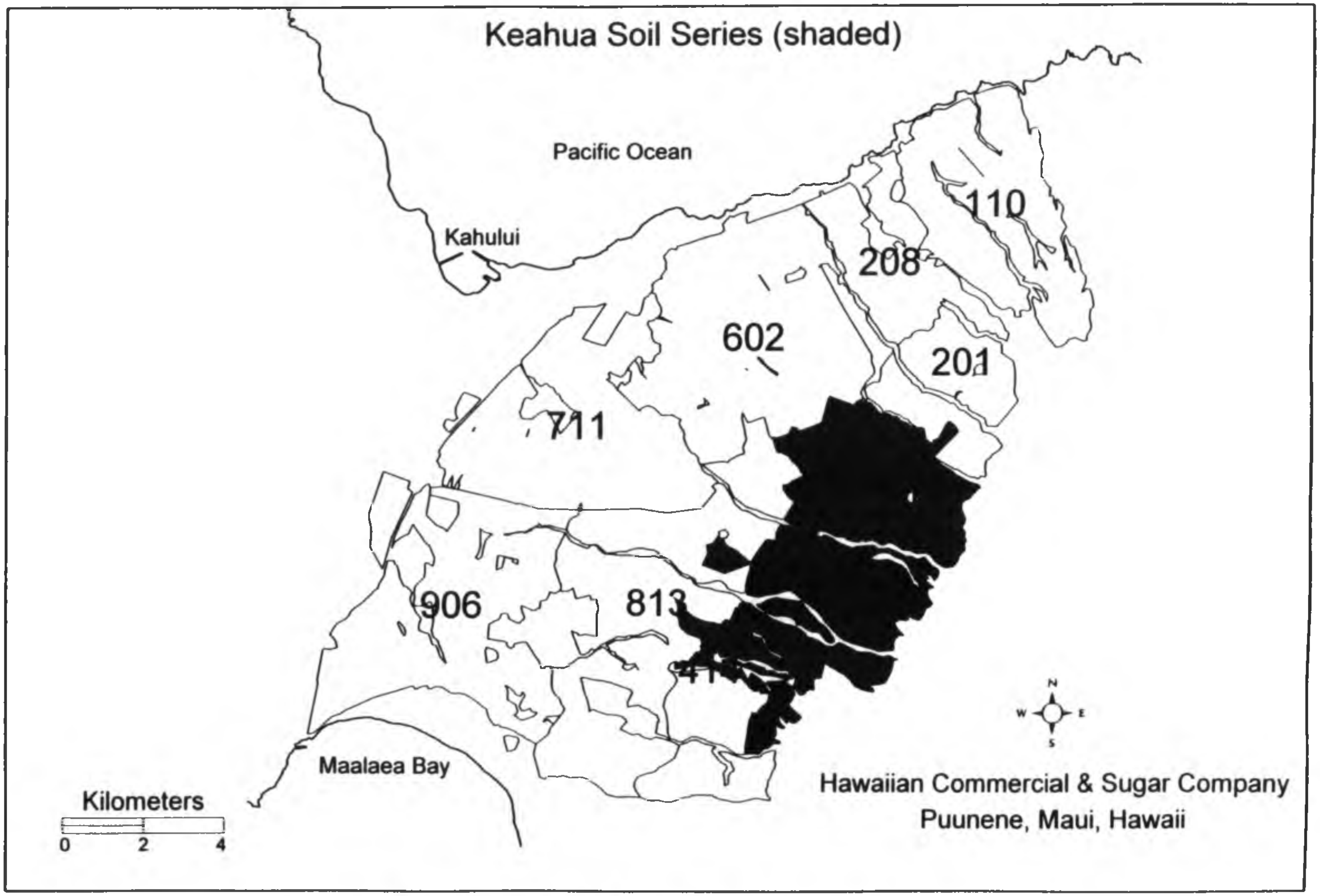


Figure 57. Map of fields with Keahua soil series.

Table 57. Furrow irrigation mean sugar yields (TSA in Mg ha^{-1}) by soil series (mill waste fields are included as a category).

Soil Series	n	Yield*
	--harvests--	--Mg ha^{-1}--
Haliimaile	9	31.96a
Keahua	338	29.13b
Molokai	273	27.75bc
Ewa	155	27.50c
Paia	268	26.91cd
Pulehu	273	26.31cde
Waiakoa	280	26.27cde
Alae	55	25.64de
Jaucas	76	25.13e
Mill	194	24.8e

*Means followed by the same letters are not significantly different at the 0.05 % probability level by Duncan's Multiple Range Test.

Table 58. Drip irrigation mean sugar yields (TSA as Mg ha^{-1}) by soil series (mill water fields are included as a category).

Soil Series	n	Yield*
	--harvests--	--Mg ha^{-1}--
Pulehu	84	32.42a
Ewa	53	32.23a
Molokai	102	32.21a
Jaucas	14	31.45ab
Keahua	209	30.96ab
Waiakoa	164	30.70abc
Haliimaile	41	30.11abcd
Alae	31	29.48bcd
Paia	139	28.40cd
Hamakuapoko	40	28.02d
Mill	6	22.15e

*Means followed by the same letters are not significantly different at the 0.05 % probability level by Duncan's Multiple Range Test.

high drip irrigation means for Pulehu, Ewa and Waiakoa, all of which are in the area with the most sunshine and lowest rainfall area of the plantation, are in contrast to their relatively low means with furrow irrigation.

Fields classified as Keahua soil series have the very highest mean soil moisture storage (SMS) values (Table 59). As mentioned above, these soils, located on the upper Haleakala side of the plantation, had the highest mean tonnes sugar hectare^{-1} with furrow irrigation. With the high SMS values, this area was irrigated less frequently. (SMS is still being used instead of using PE for irrigation scheduling. If high mean SMS in the water balance lengthens the irrigation interval for drip irrigation, plants could be stressed.) The SMS means for Paia and Hamakuapoko soil series, both silty clays, are low and are not significantly different than Jaucas and Alae means. On the basis of soil texture alone, having the SMS for clay the same as sand is surprising. The estimated rooting depth is not known.

With furrow irrigation, mean tonnes sugar hectare^{-1} was highest for soil texture class silty clay loam (Table 60). Most of the harvests were from fields with this classification. Not significantly different were means for silty clay loam and clay loam. These are soils with higher water holding capacity. The lowest yields were harvested from fields classified as sandy loam, sand, and mill waste fields. The mill waste fields receive too much nitrogen late in the crop cycle to ripen properly. The switch from furrow irrigation to drip irrigation changed the ranking of soil texture classes with sand, silt loam, and clay loam moving ahead of

Table 59. Mean soil moisture storage (SMS) values by soil series. (Note: n = the number of fields in each soil series not harvests.)

Soil Series	n	SMS*
	--fields--	--mm--
Keahua	27	113.6a
Molokai	18	101.2b
mill	11	96.1bc
Ewa	11	94.3bcd
Haliimaile	6	92.3bcde
Pulehu	18	89.5cde
Waiakoa	25	88.3cde
Jaucas	8	83.2def
Paia	22	81.5ef
Hamakuapoko	7	76.9f
Alae	5	75.2f

*Means followed by the same letters are not significantly different at the 0.05 % probability level by Duncan's Multiple Range Test.

Table 60. Furrow irrigation mean sugar yield (TSA in Mg ha^{-1}) by soil texture classes.

Soil Texture	n	Yield*
	--harvests--	--Mg ha^{-1}--
silty clay loam	1009	27.7a
silty clay	315	27.3a
clay loam	102	26.8ab
silt loam	171	26.0bc
sandy loam	55	25.6cd
sand	76	25.1cd
mill	194	24.8d

*Means followed by the same letters are not significantly different at the 0.05% probability level by Duncan's Multiple Range Test.

silty clay loam. Furrow irrigation apparently could not provide enough water to soils with low soil moisture storage located in areas of high water demand.

The fields with the highest tonnes sugar hectare^{-1} (drip) were those classified as clay loam, silt loam, and sand (Table 61). These three soil texture classes are found in the area of the plantation having the highest potential evapotranspiration (primarily fields numbered in the 900's). Most of the other harvests were from fields classified as silty clay loam. In Fig. 58, the large central part of the plantation is dominated by the soil texture silty clay loam (Oxisols and Mollisols). Pan groups 107 (208), 110 and 201 are dominated by Paia silty clay, Hamakuapoko silty clay and Hailiimaile silty clay (Fig. 59). The other small areas of silty clay are Ewa soil series.

After soil types were classified by field, soil phase and texture could be listed as field attributes. Soils with textures sand, sandy loam, silt loam, and clay loam are located primarily in pan group 906 with some in adjoining pan groups 813 and 711(Fig. 60). Sand and silt loam had the most drip irrigation water applied (Table 62). Gross water applied has not been adjusted for rainfall (Table 63). The sands are located in pan evaporation group 906. The silty clay soil texture class is found in the wettest area of the plantation.

No documentation was given on how the soil moisture storage values were derived for the 157 fields. Values for individual fields have been adjusted as a way to make adjustments in irrigation. The values do not necessarily reflect measured soil characteristics. The highest soil moisture storage values are

Table 61. Drip irrigation mean sugar yield (TSA in Mg ha^{-1}) by soil texture classes.

Soil Texture	n	Yield*
	--harvests--	--Mg ha^{-1}--
clay loam	29	33.3a
silt loam	55	31.9ab
sand	14	31.5abc
silty clay loam	517	31.2bc
sandy loam	31	29.5c
silty clay	231	28.8c
mill	6	22.2d

*Means followed by the same letters are not significantly different at the 0.05% probability level by Duncan's Multiple Range Test.

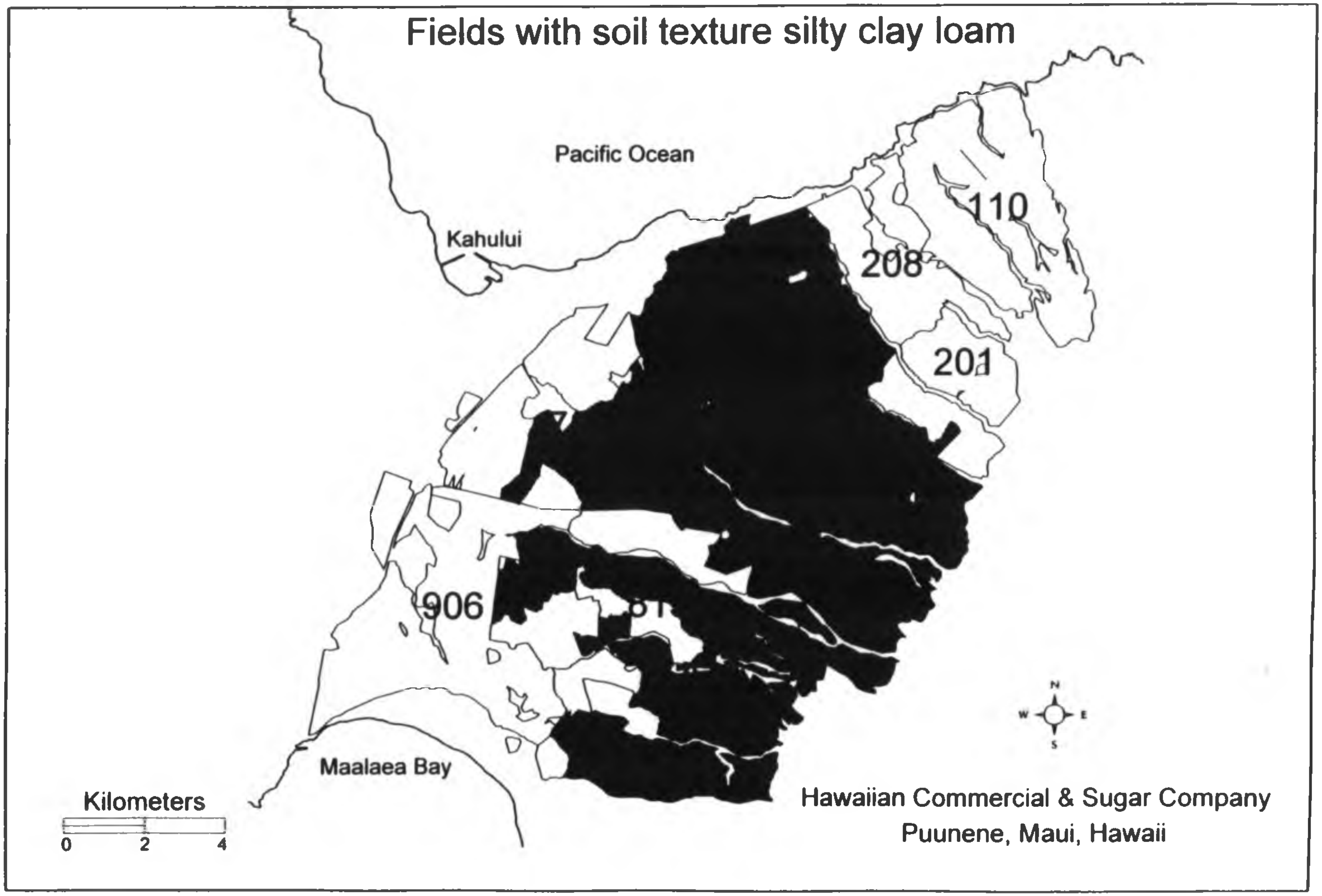


Figure 58. Map of fields with soil texture silty clay loam.

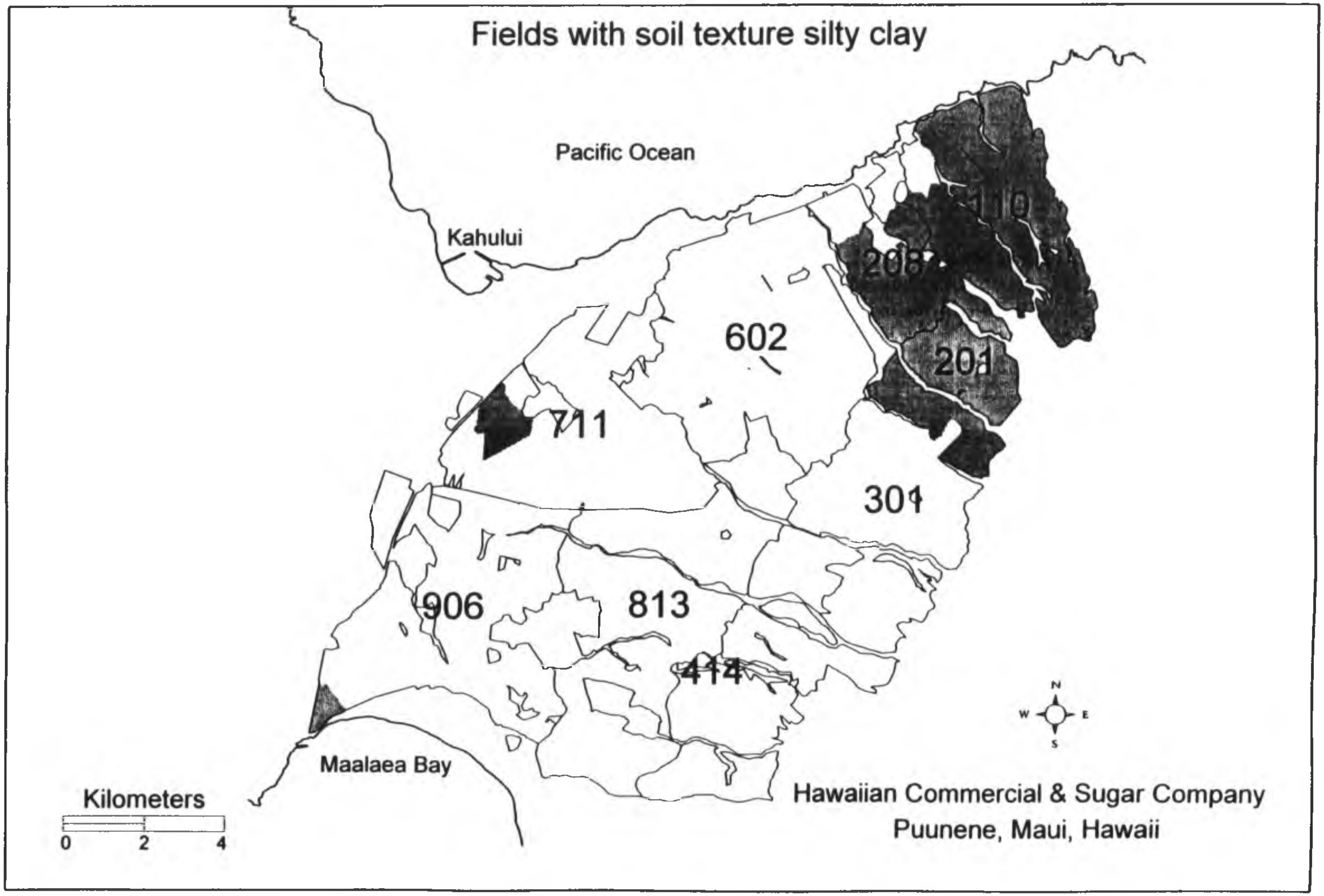


Figure 59. Map of fields with soil texture silty clay.

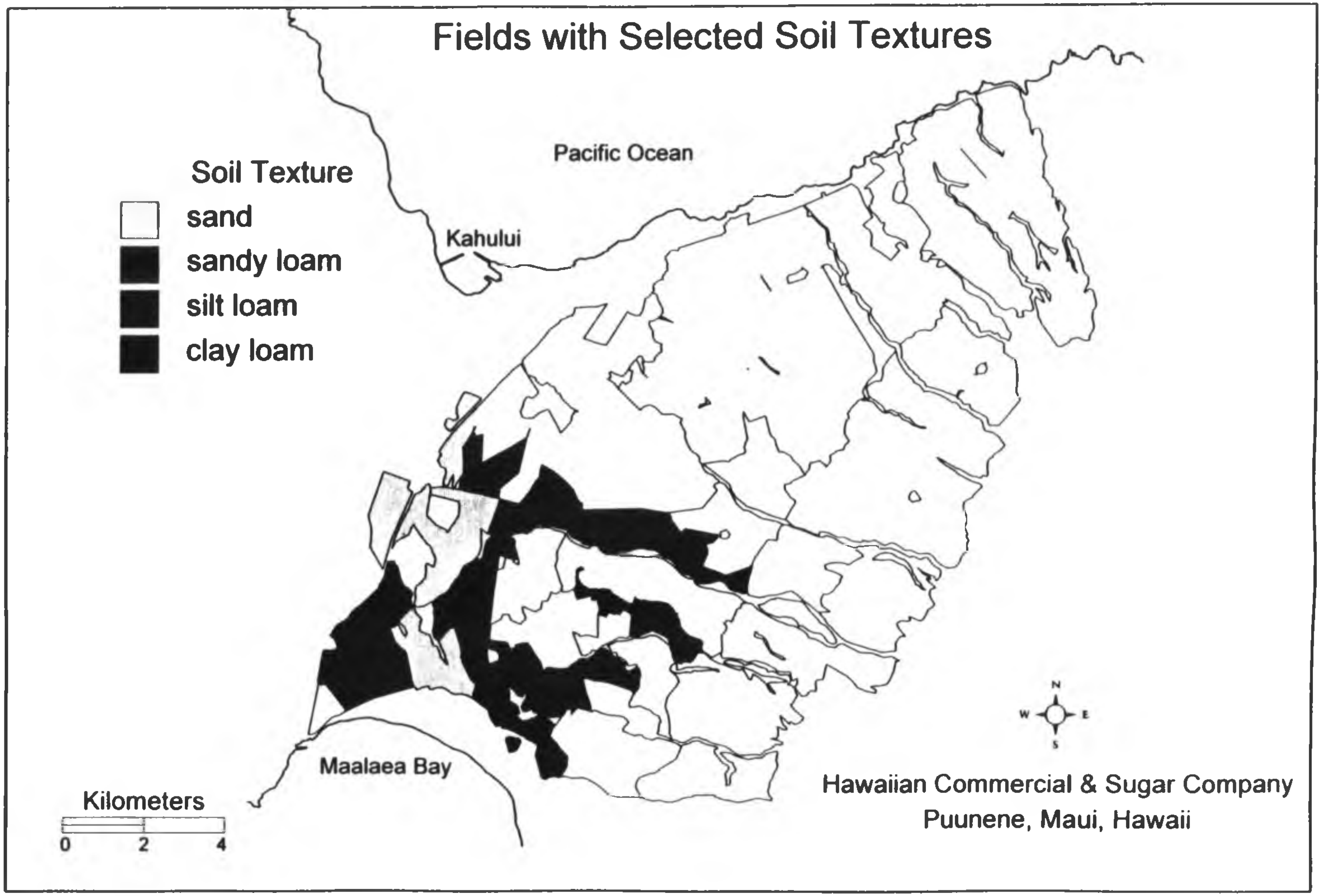


Figure 60. Map of fields with selected soil textures.

Table 62. Furrow irrigation water applied (IRRI) for the complete crop cycle. Fields are grouped by soil texture with mill waste fields separate.

Soil Texture	n	Irrigation*
	--harvests--	--rounds--
sand	76	42.6a
clay loam	102	40.5b
sandy loam	55	39.1bc
silt loam	171	38.9bc
mill	194	37.9cd
silty clay	315	36.3cd
silty clay loam	1009	35.4e

*Means followed by the same letters are not significantly different at the 0.05% probability level by Duncan's Multiple Range Test.

Table 63. Drip irrigation mean gross water applied (GW_APPL) for the complete crop cycle. Fields are grouped by soil texture with mill water fields as a category.

Soil Texture	n	Irrigation*
	--harvests--	--mm--
sand	14	5103.1a
silt loam	55	4652.8ab
clay loam	29	4436.1b
silty clay loam	517	4313.0b
sandy loam	31	4302.4b
silty clay	231	3346.6c

*Means followed by the same letters are not significantly different at the 0.05% probability level by Duncan's Multiple Range Test.

assigned to fields classified silty clay loam (one-half of the plantation) in Table 64. Silty clay soil moisture storage values are as low as those for sand and sandy loam.

Mill waste fields are located near Paia and Puunene mills (Fig. 61). Mill waste fields receive too many nutrients to ripen properly. They behave more like one another than fields with the same type of soils with respect to yield variables. For this reason they are in a separate category. Soil phase is mapped in Fig. 62. Pan groups 813 and 414 have the most difficult to manage soil.

Pan Groups are based on current pan assignments. Fields given the same daily values for potential evapotranspiration, whether estimated by evaporation pan or by the modified Penman equation, combine to form 9 different regions (Table 65). Differences in planting data and age of the crop at harvest are reflected in differences in potential evapotranspiration by harvest within the group even though the daily potential evapotranspiration within each group is the same. Pan Groups 301 and 414 of the Keahua Irrigation Division have the highest SMS means. The Keahua Division has soils of the Keahua and Waiakoa soil series. Waiakoa fields were added to the division as part of drip expansion. Pan groups 602 (Molokai soil series), 201, and 711 (near Puunene factory) have mean SMS values significantly below those of Keahua. Pan groups 906 and 813 are in high potential evapotranspiration areas and pan groups 107 (208) and 110 are in the wetter Paia end of the plantation.

Table 64. Mean soil moisture storage (SMS) values by soil texture class. (Note: this is based on field means not harvest data)

Soil Texture	n	SMS*
	--fields--	--mm--
silty clay loam	78	100.8a
mill	11	96.1ab
silt loam	12	89.2abc
clay loam	6	87.2abc
sand	8	83.2bc
silty clay	38	83.1bc
sandy loam	5	75.2c

*Means followed by the same letters are not significantly different at the 0.05% probability level by Duncan's Multiple Range Test.

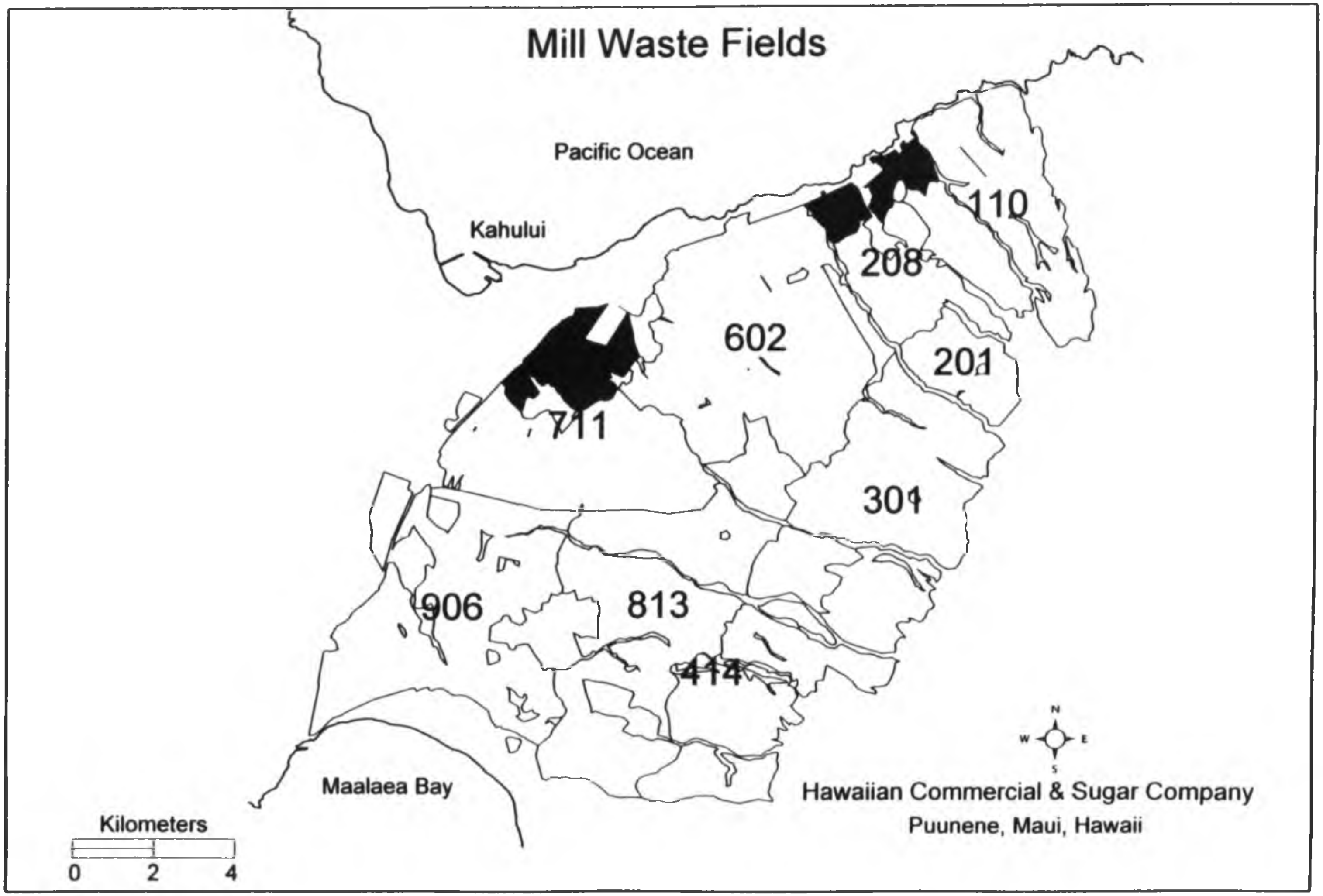


Figure 61. Map of mill waste fields.

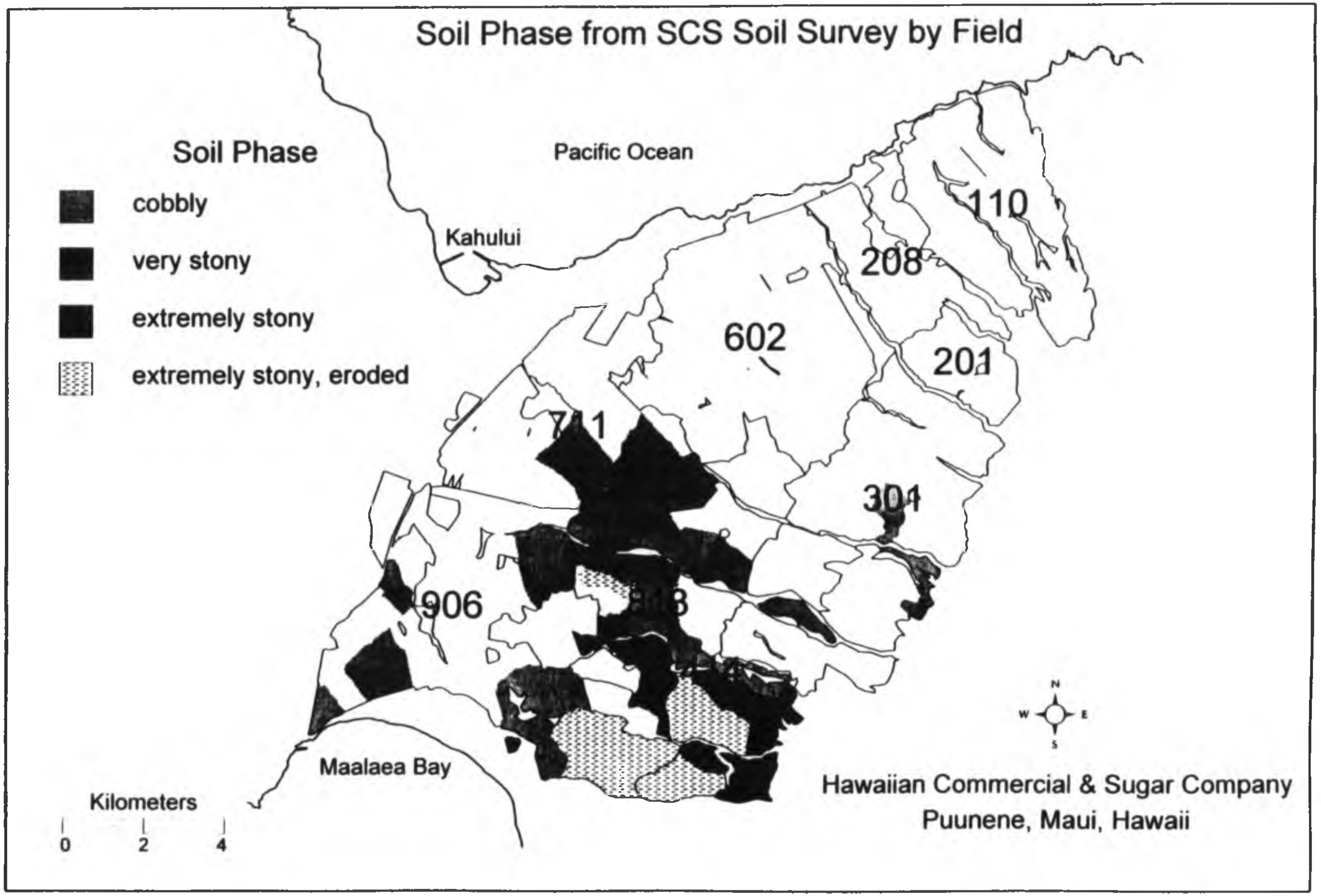


Figure 62. Map of soil phase.

Table 65. Mean soil moisture storage (SMS) for fields with the same potential evaporation assigned. (Note: n = the number of fields in each pan group not harvests.)

Pan Group	n	SMS*
	--fields--	--mm--
301	17	114.5a
414	13	112.9a
602	20	100.9b
201	5	95.5bc
711	20	93.0bcd
906	20	87.2cde
813	28	85.1de
107	13	83.8de
110	22	78.5e

*Means followed by the same letters are not significantly different at the 0.05 % probability level by Duncan's Multiple Range Test.

Pan groups 201 and 301 are at the highest mean elevations of the plantation with mean elevation of 240 and 229 meters, respectively in Table 66. The lowest mean elevations, all below 60 meters, are found in pan groups 602, 711, and 906. Pan groups 110 and 201 had identical monthly evaporation values from 1989-1993 and, therefore, were one group during that time period even though they had very different means.

Changes in the late 1980s

Yield, Age, and Water Efficiency

Despite the obvious improvement in yield with drip irrigation, there were some changes in relative ranking of different areas within the plantation and water use efficiency values lower than expected. Further examination of sugarcane production since drip conversion seemed to be warranted. In the late 1980s, 10 years after the beginning of drip conversion, more technological changes occurred at the plantation as well as increased pressure to monitor ground water and cane burning. Since 1989, yields and water use efficiency have been down. In addition, the age at harvest has been lower.

Table 67 is a comparison of mean tonnes sugar/hectare (TSA) by year for drip irrigation data only. The number of harvests (n) is lower from 1978 to the early 1980s as drip conversion was gradual. What is striking here is the low ranking of yields in the 1990s. The lowest ranking years were 1978, when only

Table 66. Mean elevation (ELEV) for fields with the same evaporation assigned. (Note: n = the number of fields in each pan group not harvests.)

Pan Group	n	Elev.*
	--fields--	--m--
201	5	240.4a
301	17	229.3a
414	13	178.9b
110	22	133.0c
813	28	82.4d
107	13	81.0d
602	20	59.9de
711	20	38.0e
906	20	31.4e

Note: 110 and 201 had identical data from 1989-1994
*Means followed by the same letters are not significantly different at the 0.05 % probability level by Duncan's Multiple Range Test.

Table 67. Drip irrigation mean sugar yield (TSA as Mg ha^{-1}) by year.

Year	n	Yield*
	--harvests--	--Mg ha^{-1}--
1979	18	33.78a
1987	65	33.47ab
1983	43	32.11abc
1984	55	31.64bc
1986	61	31.56bc
1989	72	31.37bc
1988	68	31.30c
1980	24	31.14c
1985	61	30.74cd
1982	32	30.46cd
1990	69	30.30cd
1981	32	30.24cd
1993	73	30.21cd
1994	68	28.70de
1992	64	28.07e
1978	13	27.84e
1991	71	27.83e

*Means followed by the same letters are not significantly different at the 0.05 % probability level by Duncan's Multiple Range Test.

13 fields had been converted, and 1991 with 71 fields and a mean of 17.83 Mg ha^{-1}. The mean harvest ages for the same years are ranked in Table 68. The year with the lowest ranking years were 1978, when only 13 fields had been converted, and 1991 with 71 fields and a mean of 27.83 Mg ha^{-1}. The mean harvest ages for the same years are ranked in Table 68 The year with the lowest mean harvest age, 22.02 months, was 1991. At the center of Table 68, 1987, 1988, and 1989 all have mean harvest ages around 24.5 months. As seen in Table 69, these years had good yields. Drip irrigation mean tonnes cane $hectare^{-1}$ values are listed in Table 69. The lowest means in descending order are 1989, 1993, 1990, 1994, 1992, and 1991. In Table 70 tonnes cane $hectare^{-1}$ has been divided by gross water (irrigation) water applied to compare water efficiency as defined by the ratio of water applied to cane produced. Four of the highest ranked years (1986, 1987, 1984, 1983) were also high yielding. The 1990s were all low ranking. They all share the letter h indicating they are not significantly different at the 0.05% level using Duncan's Multiple Range Test.

Table 71 also represents a test of water efficiency except that effective water (effective rainfall + effective irrigation) was used instead of gross water applied. The years with the lowest means are 1988-1989.

In other analyses, including plots of raw data over time and maps of individual harvests overtime, it was apparent that some kind of perturbation occurred in the late 1980s. The most outstanding year on record was 1987. Data

Table 68. Drip irrigation yearly mean harvest age (months).

Year	n	Age
	--harvests--	--months--
1980	24	27.10a
1982	32	26.21b
1983	43	25.82bc
1981	32	25.25cd
1979	18	25.23cd
1984	55	25.00de
1988	68	24.61def
1987	65	24.56def
1989	72	24.46def
1985	61	24.38ef
1994	68	24.02fg
1986	61	24.01fg
1993	73	23.83fg
1978	13	23.23gh
1990	69	22.87h
1992	64	22.75h
1991	71	22.02i

*Means followed by the same letters are not significantly different at the 0.05 % probability level by Duncan's Multiple Range Test.

Table 69. Drip irrigation mean tonnes cane/hectare by year.

Year	n	Cane
	--harvests--	--Mg ha^{-1}--
1979	18	274.5a
1980	24	268.7a
1983	43	250.2b
1984	55	241.0bc
1987	65	239.9bc
1982	32	238.5bcd
1981	32	235.4bcde
1986	61	233.6bcde
1985	61	231.7cdef
1978	13	226.2cdef
1988	66	224.4cdef
1989	72	221.7defg
1993	73	217.8efg
1990	69	215.8fgh
1994	62	207.3ghi
1992	64	200.9hi
1991	71	192.2i

*Means followed by the same letters are not significantly different at the 0.05 % probability level by Duncan's Multiple Range Test.

Table 70. Drip irrigation mean tonnes cane hectare/gross water applied

Year	n	TCGW*
	--harvests--	--Mg/mm--
1986	61	0.0674a
1987	65	0.0656ab
1985	61	0.0646abc
1983	43	0.0642abc
1984	55	0.0608abcd
1982	32	0.0591bcde
1978	13	0.0585cdef
1980	24	0.0584cdef
1981	32	0.0583cdef
1989	72	0.0562defg
1993	73	0.0558defgh
1979	18	0.0557defgh
1991	71	0.0523efgh
1992	64	0.0522efgh
1990	69	0.0514fgh
1988	66	0.0496gh
1994	62	0.0489h

*Means followed by the same letters are not significantly different at the 0.05 % probability level by Duncan's Multiple Range Test.

Table 71. Drip irrigation mean tonnes cane hectare/effective water

Year	n	TCEW*
	--harvests--	--Mg/mm--
1979	18	0.0863a
1983	43	0.0838ab
1978	13	0.0834ab
1981	32	0.0801bc
1987	65	0.0796bc
1980	24	0.0779cd
1985	61	0.0775cde
1986	61	0.0768cdef
1984	55	0.0764cdef
1982	32	0.0751cdef
1988	66	0.0738defg
1992	64	0.0720efg
1993	73	0.0713fg
1989	72	0.0692gh
1991	71	0.0684gh
1994	62	0.0654hi
1990	69	0.0616i

*Means followed by the same letters are not significantly different at the 0.05 % probability level by Duncan's Multiple Range Test.

and results were reviewed comparing conditions before 1987 with the conditions that preceded the low yields and reduced water use efficiency in the 1990s.

Plantation management had clearly stated their current pressing concern is "Where to put water when water is short?". There was no indication that a sudden plantation-wide change in the soils had taken place either in spatial analysis or the in the soil analysis graphs, at least through 1992. The most sweeping technological change in the late 1980s was the discontinuation of the pan evaporation network and the installation of an automatic weather station network designed for predicting the likelihood of winds blowing cane smoke to residential areas.

The following section explores the pan evaporation network, potential evapotranspiration, and the climate of Maui.

Pan Evaporation

The use of evaporation pans has a long history at HC&S. Pans were not always easy to keep up. Cows could drink the water, sprinklers could add water, or there could be a slow leak. Labor is required to record the data. Ekern (1970) found that for periods of ten days or longer, pan evaporation compared favorably to evaporation as measured by a lysimeter. Therefore, evaporation pans are not recommended for daily evaporation values.

Figure 63 is a map of the fields where evaporation pans were located in the 1980s before pans were discontinued. Pan groups 906, 813, and 602 have three fields each with evaporation stations. From the most northern station in pan group

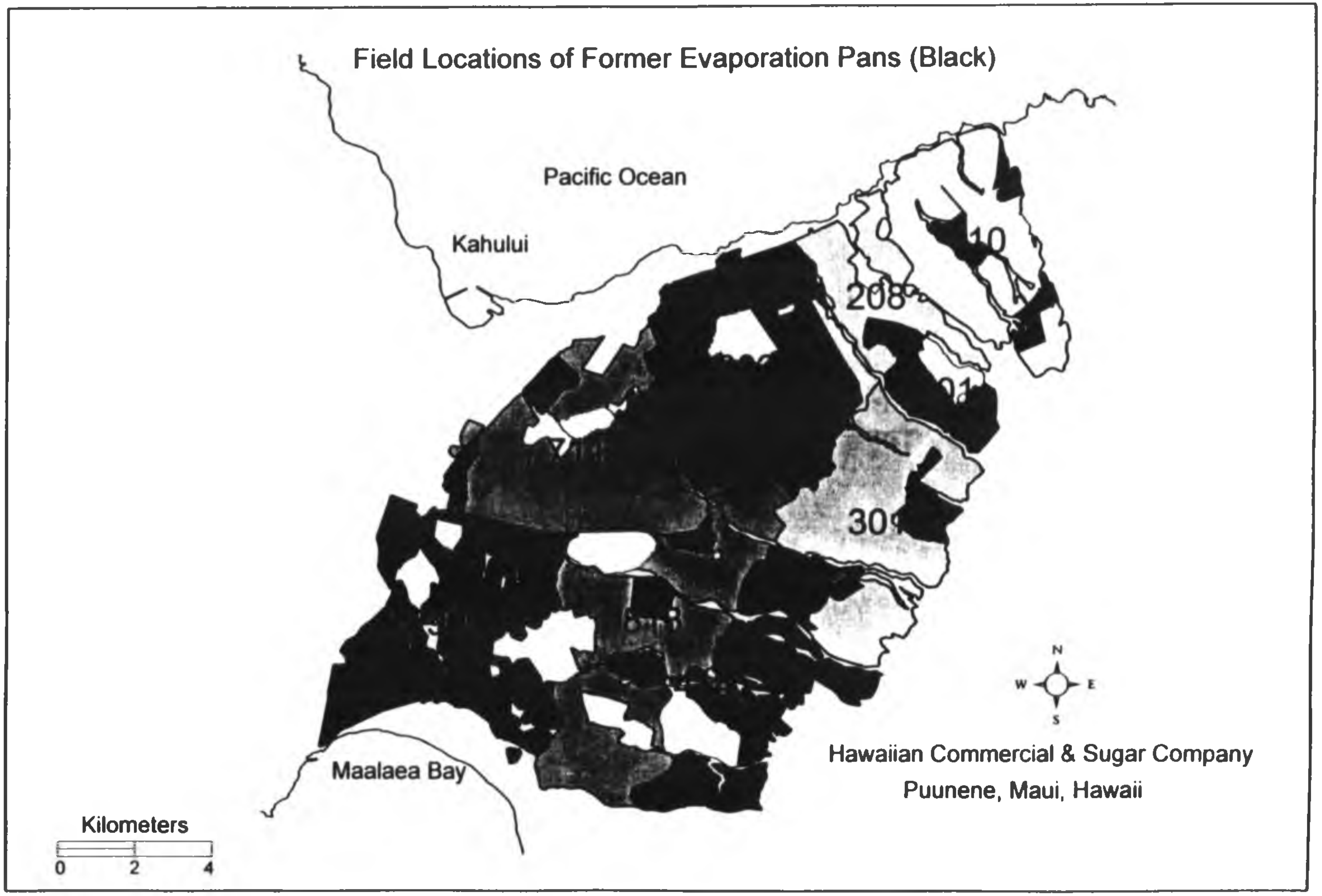


Figure 63. Map of field locations of former evaporation pans.

110 down through 208. 602, and 813 there are 7 station in a transect from wetter to drier. In all there are 18 stations. The map of annual rainfall (Fig. 64) indicates the rainfall pattern with isohyets in millimeters. The northeastern (pan 110) is wetter, 750 - 1500 mm of rain annually, but this is dry compared to the windward side of Haleakala which has rainfall up to 7000 mm annually (and provides the surface irrigation water). Much of the plantation receives 500 mm or less of rainfall a year.

Mean monthly pan evaporation for a selection of stations on Maui is shown in Fig. 65. Station 415 (field 301) has a very distinct summer peak in July, higher than any other of the stations plotted. Station 310.10, field 906, also has summer evaporation values twice that of winter values. Chang (1963) computed a monthly water balance various fields at different sugarcane plantations, including fields 405 and 913 of HC&S Plantation (Fig. 66). There is almost no rainfall in the summer and the large water deficit seen in the monthly water balance illustrates why the plantation relies 100% on irrigation in the summer.

Nullet (1987) studied evaporation on tropical islands including Maui. Advection is the transfer of heat from one area to another, increasing evaporation (and plant stress) without an increase in solar radiation. When wind comes onshore from cooler water there is cooling or negative advection. Fig. 1 (in Fig. 67) of Nullet's article (1987) illustrates the contribution to evaporation by advection on an island in a transect from windward to leeward. HC&S, on the leeward side of the island of Maui, would have the Paia Division toward the

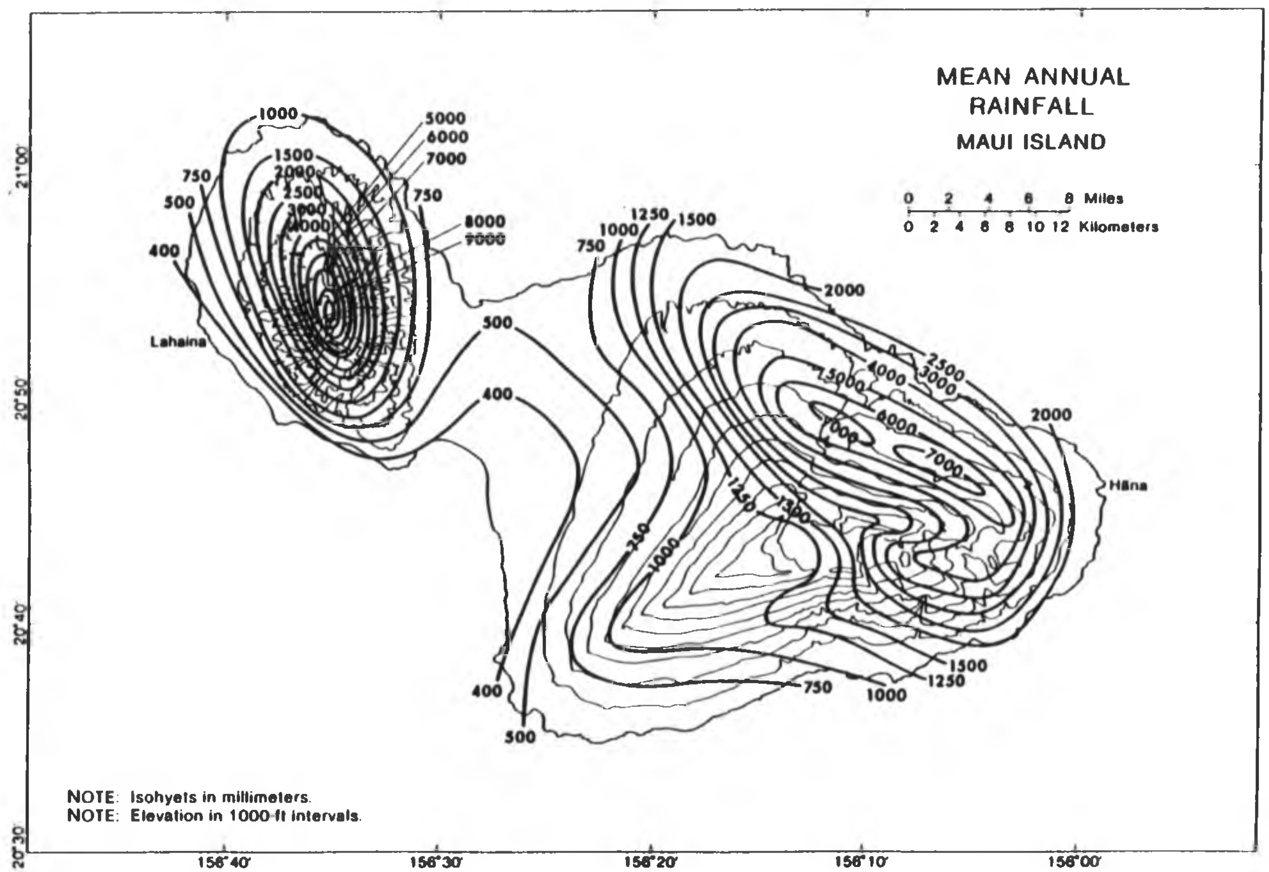


Figure 64. Map of mean annual rainfall Maui Island (Giambelluca, et al., 1986)

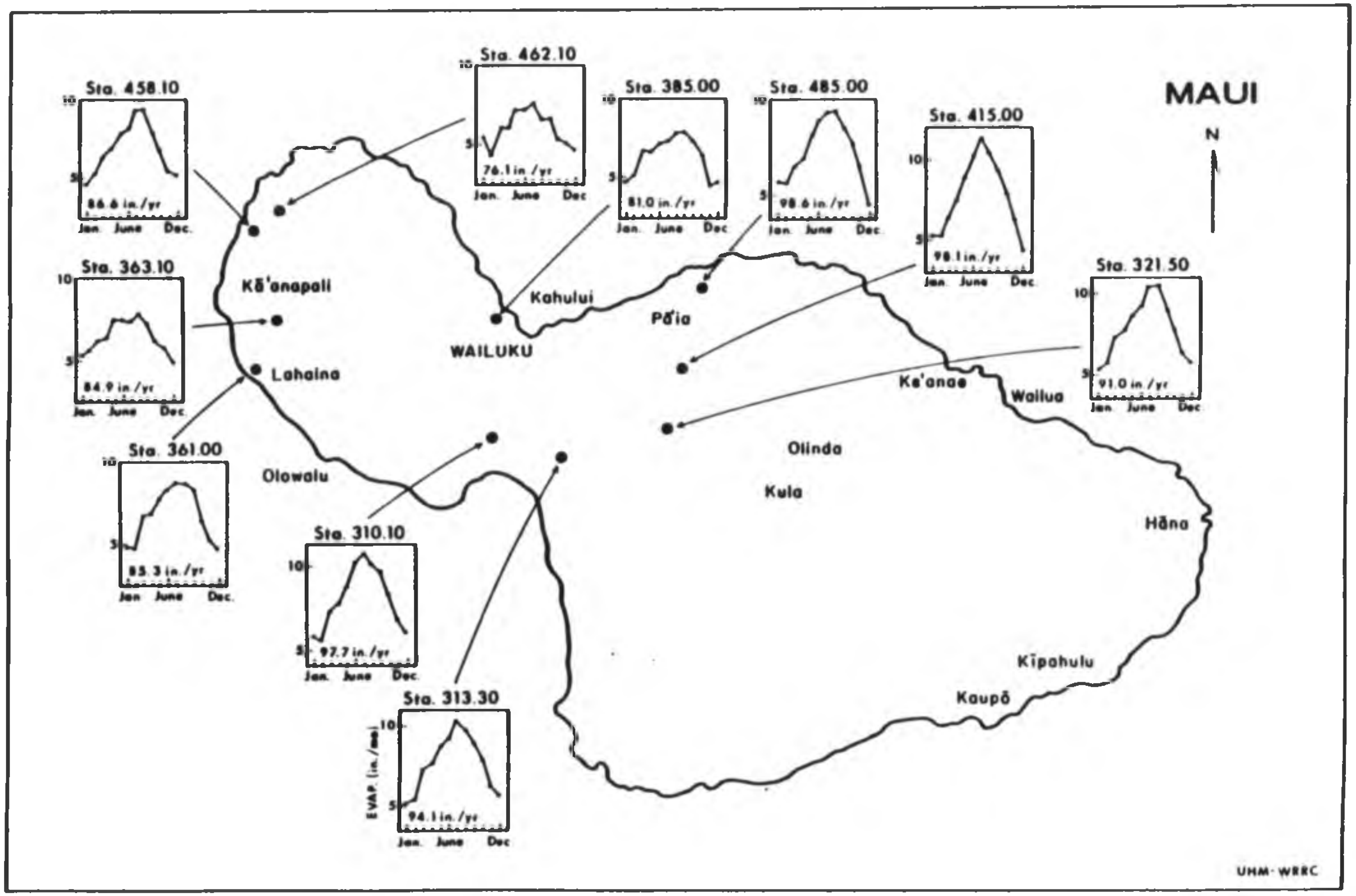
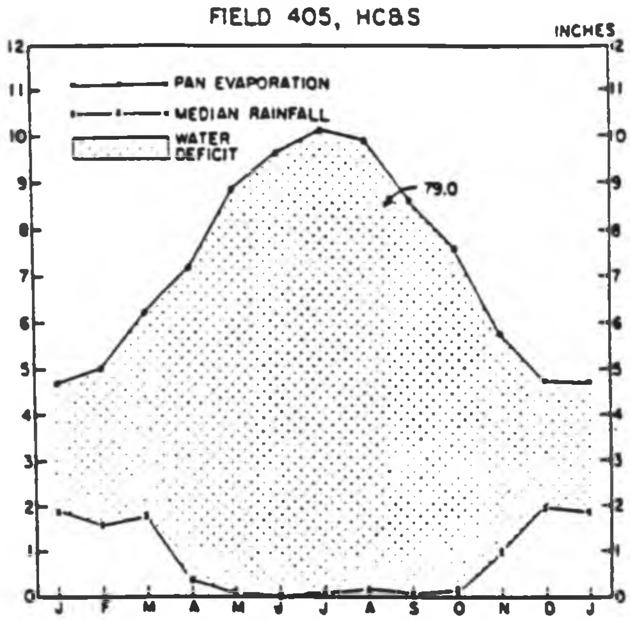


Figure 65. Pan evaporation Maui Island (Ekern and Chang, 1985)



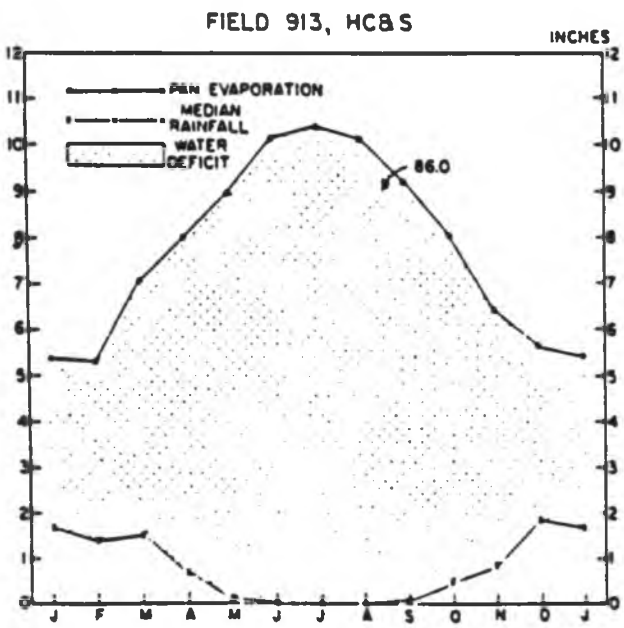


Figure 66. Monthly water balance for fields 405 and 913 (Chang, 1961)

middle of the graph with Keahua Division along a line of rising advection toward leeward if the map were superimposed on the annual pattern of advection.

Advection was estimated by calculating the difference between evaporation calculated with the Priestley-Taylor equation and pan evaporation. Priestley-Taylor is similar to the Penman equation in that it depends primarily on solar radiation in calculating evaporation. Fig. 2 (in Fig. 67) gives a comparison of Priestley-Taylor and pan evaporation monthly evaporation for 5 stations from windward to leeward. The residual pattern (top) indicates the advection gradient. Station 396, Kahului has the greatest positive residual (advection). (Nullet, 1987)

Nullet (1987) observes that the Penman equation would behave similarly to Priestley Taylor in not accounting for advection. Chang (1963) tested the Penman equation in field 906 and concluded the estimates were 89% lower than pan. Chang (1968) does not recommend the Penman equation for areas with advection. Doorenbos and Pruitt 1977 also caution against using Penman where daytime winds are stronger than nighttime winds. The Penman equation is usually mentioned in the context "well-irrigated" (Doorenbos and Pruitt, 1977). Advection is not problem under well- irrigated conditions. Dry ground heats up much more that wet ground. Nullet (1987) estimates that in the saddle of Maui in June, the Priestley Taylor method can underestimate evaporation by 2.8 mm/day.

An interesting implication of the comparison of monthly evaporation from windward to leeward (Fig. 2 in Fig. 67) and the residual described by Nullet (1987) is that there is spatial variation in how models fit. Plantation management

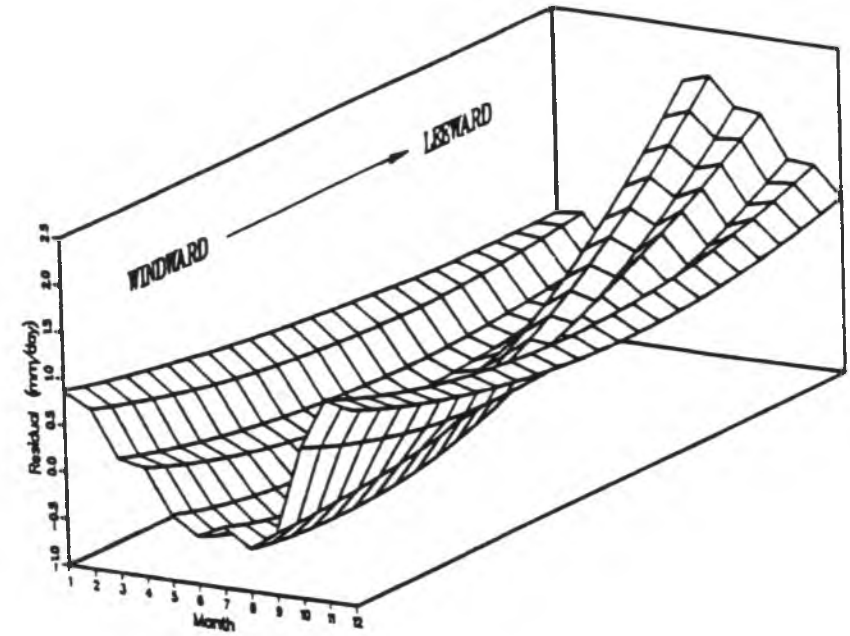


Fig. 1. Pattern of annual advection at evaporation sites in the Hawaiian Islands. Forty-nine sites were ranked by differences between summer and winter advection. Advection is represented by the residual term between measured evaporation and evaporation estimates based on solar radiation. A second order polynomial was then fit to the ranked values for each month to produce the graph. The advection pattern grades from negative in summer at windward sites to positive in summer at lee sites.

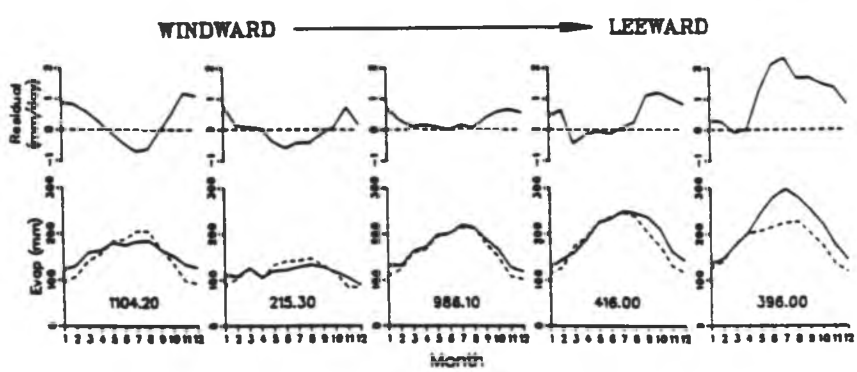


Fig. 2. Examples of measured and estimated evaporation and the corresponding residual pattern show the gradient in advection pattern from windward to leeward sites. Solid lines are measured pan evaporation and dashed lines are evaporation estimated by the Priestley-Taylor method. The numbers shown are State of Hawaii climate station identifiers.

Figure 67. Pattern of annual advection at evaporation sites (Nullet, 1987)

has said they have water distribution problems when water is short. but when they have water there is no problem. Therefore, it doesn't seem to be a physical water distribution problem. The modified Penman model for evaporation may fit well when water is not limiting and not fit under conditions where water is short and the cane is not well-irrigated..

Figures 68 and 69 illustrate sample distribution patterns of pan evaporation for 1980 and 1981. Evaporation increases along low elevation from 110 < 208 < 602 < 711 < 906. Pan group 301 also has high evaporation. Figure 70 shows the pattern of a dry year, 1984. The range of evaporation is smaller and the magnitude greater. Pan group 110 evaporation values are as high as those for 208, 201, 602, 301, and 711.

Pan evaporation (mm) by month is plotted (Fig. 71) for station 310.1 (field 906). There is a distant summer peak. The range of values is an indication of variation in evaporation between years, as well as measurement error. Figure 72 is a graph of pan evaporation (mm) by month for station 415 (field 301) showing a marked peak in June, July, and August.

Automatic Stations

Field locations for the automatic stations are plotted in Fig. 73. There are additional stations in the wind network outside the sugarcane growing areas. Each pan group, comprised of twenty or more fields, is represented by only one station. With fewer stations collecting information over the 14, 500 ha plantation, the

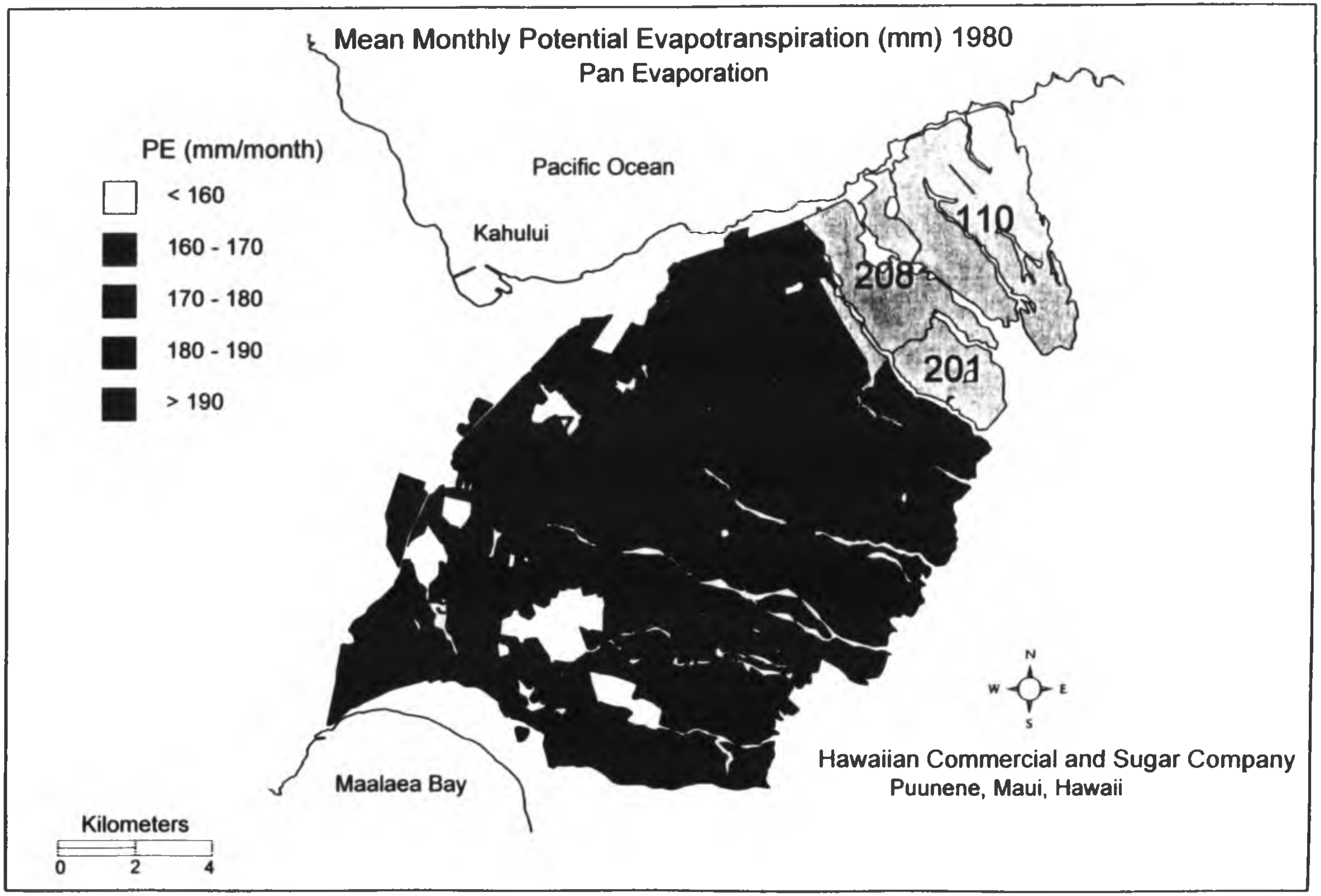


Figure 68. Map of mean monthly pan evaporation (mm) 1980.

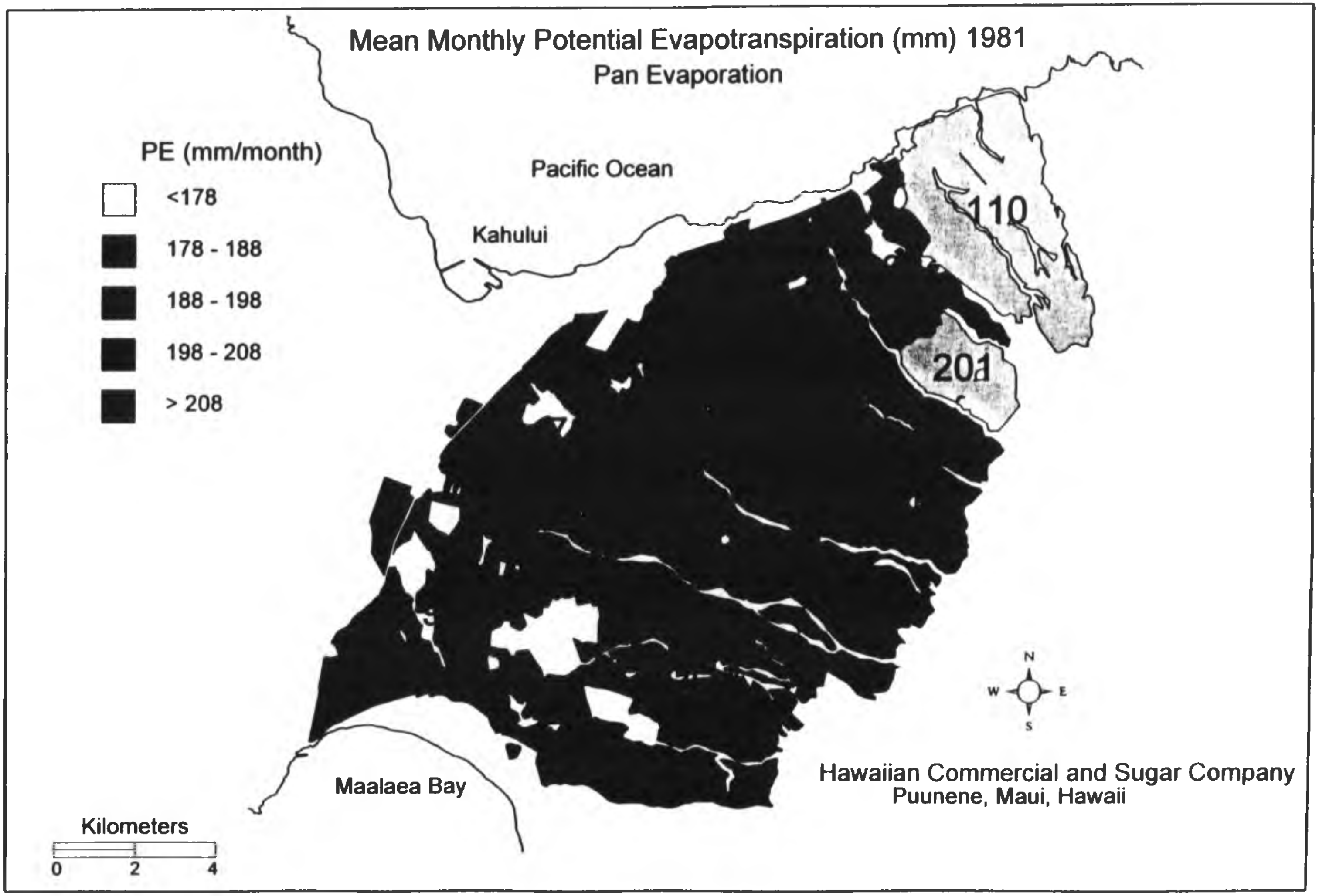


Figure 69. Map of mean monthly pan evaporation (mm) 1981.

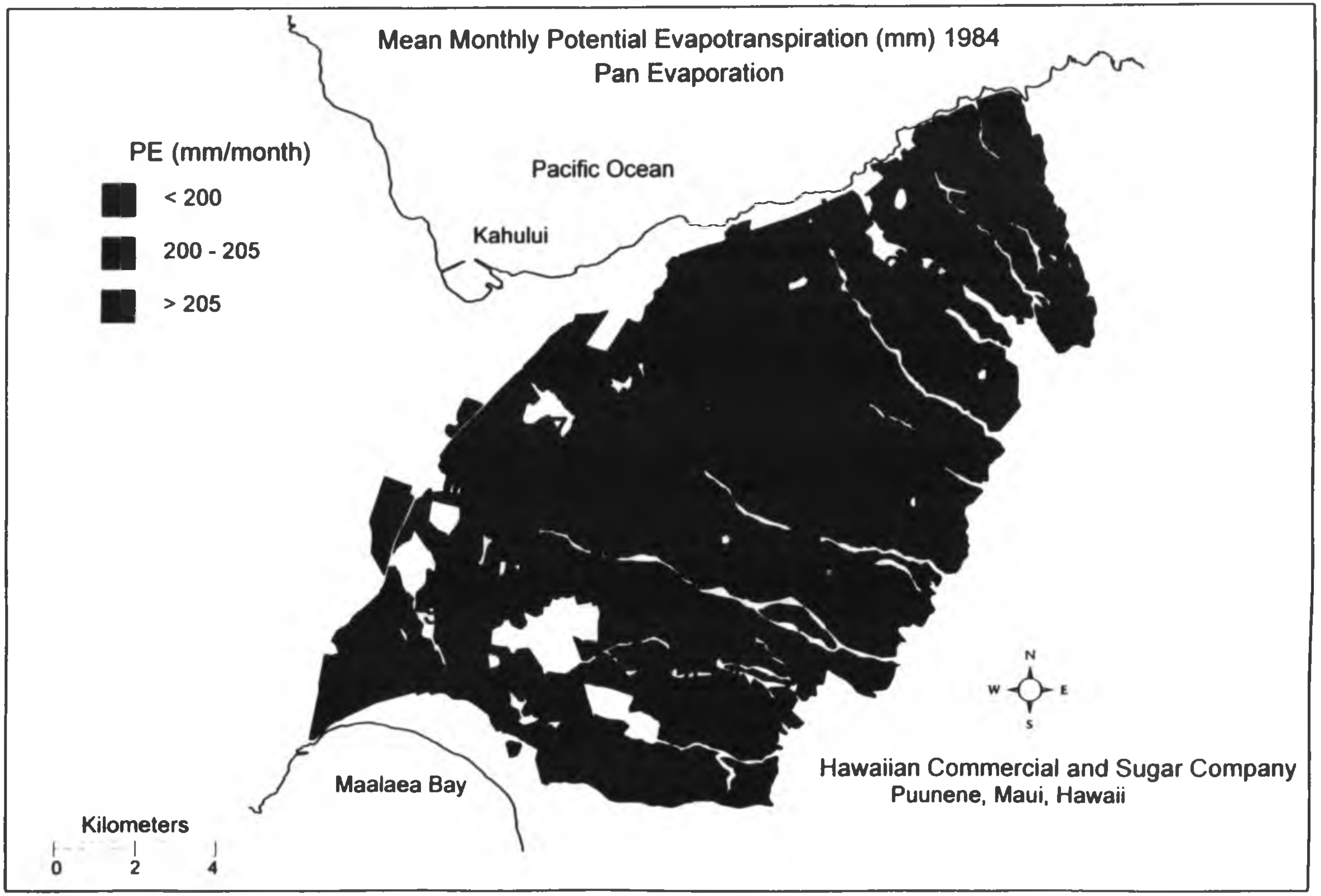


Figure 70. Map of mean monthly pan evaporation (mm) 1984.

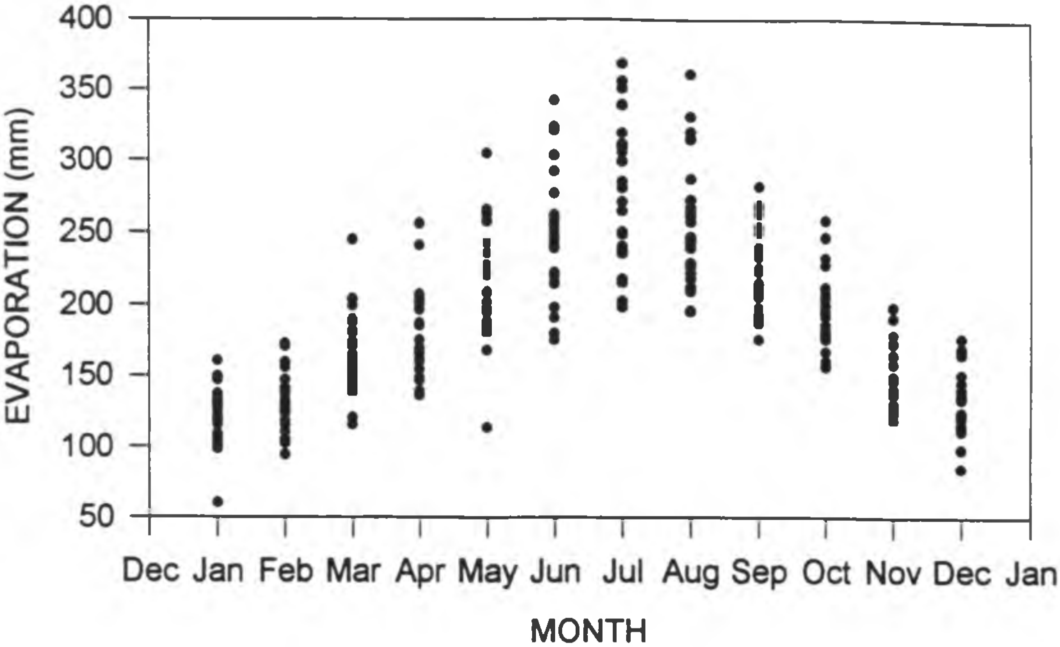


Figure 71. Mean monthly pan evaporation (mm) for field 906.

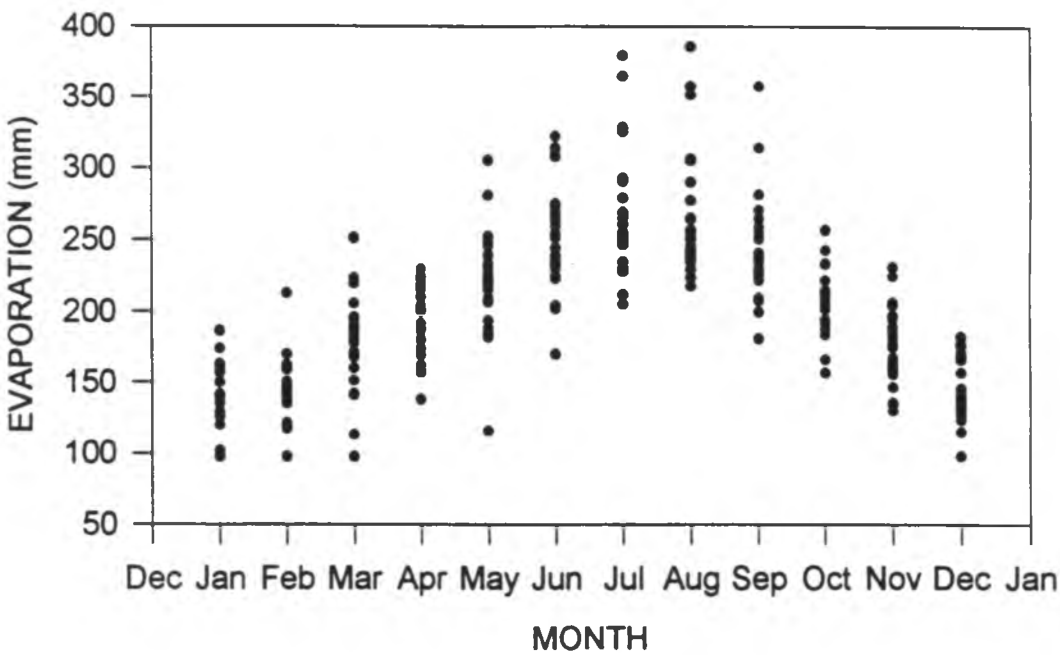


Figure 72. Mean monthly pan evaporation (mm) for field 301.

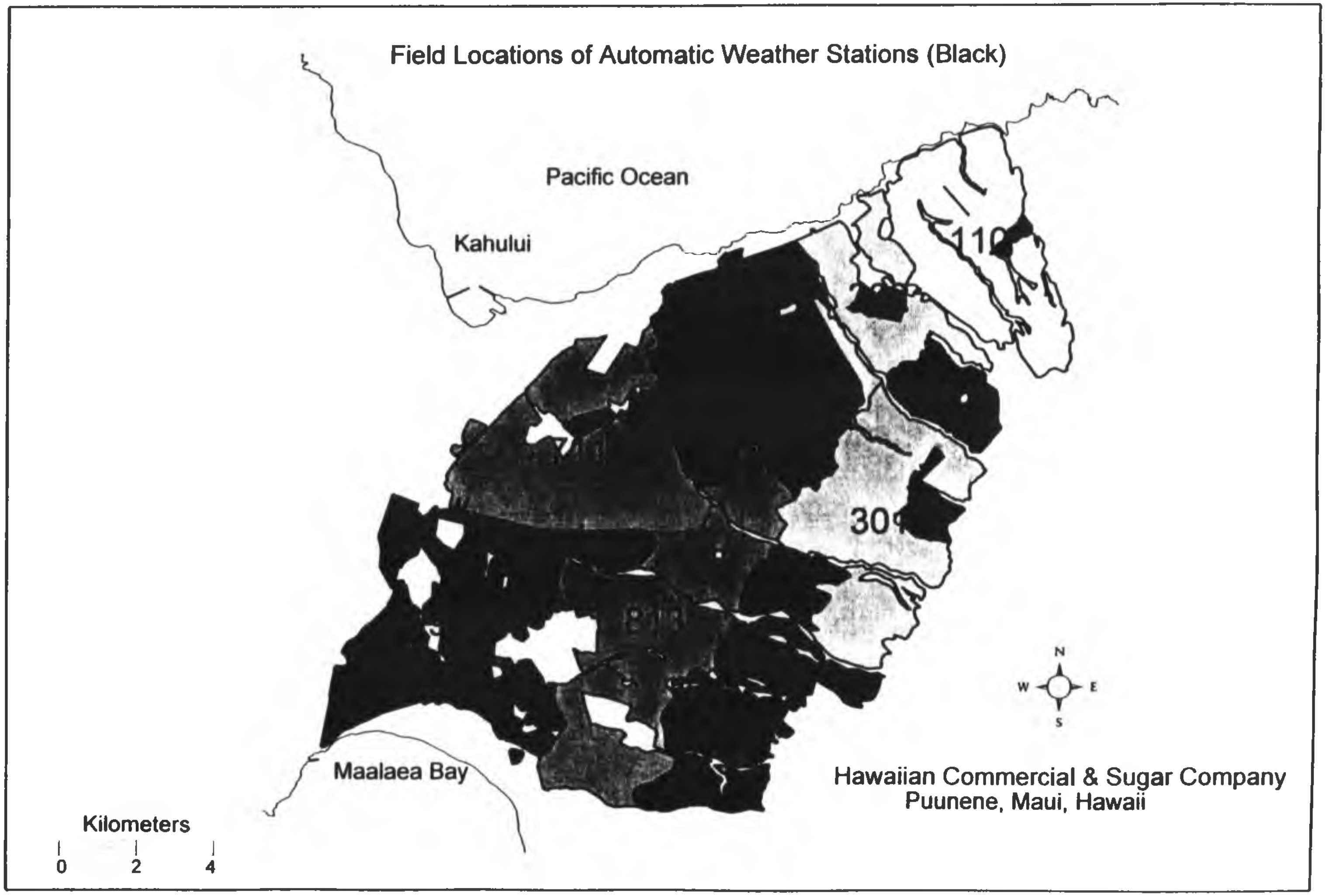


Figure 73. Field locations of automatic weather stations.

amount of spatial information lost when a station is not functioning and weather data is borrowed from elsewhere is greater.

Monthly evaporation data for pan evaporation and, beginning in the late 1980s, PE estimated using the modified Penman equation are plotted for May in Fig. 74. The first estimates based on automatic stations are very tightly bunched, with not much of a range in variability (1986-89). In 1993 several of the stations seem to be moving away from the others. Figure 75 is the same type of graph but with October data. The data for 1994 looks out of line from the previous 33 years of data.

The spatial pattern of PE by pan group mapped for 1992 (Fig. 76) is different from patterns seen with data from evaporation pans. Pan group 602 not 110 has the lowest estimates. Pan group 201 and 110 had identical values. Which pan group had the original values is not known. Monthly data is still recorded by the pan stations locations even though it is calculated for data collected from the automatic station location. This is reason to investigate daily data rather than monthly. Transferring weather from one location to another results in a loss of spatial information. The legend of the map of PE 1994 (Fig. 77) does not indicate the lowest and highest values, but the range is more than 60 mm. It may be worth investigating if the solar radiation sensor is drifting, increasing the high values or reducing the lows.

Figure 78 gives modified Penman evaporation estimates for field 906. The absence of a peak in or around July may be caused by a failure of the modified

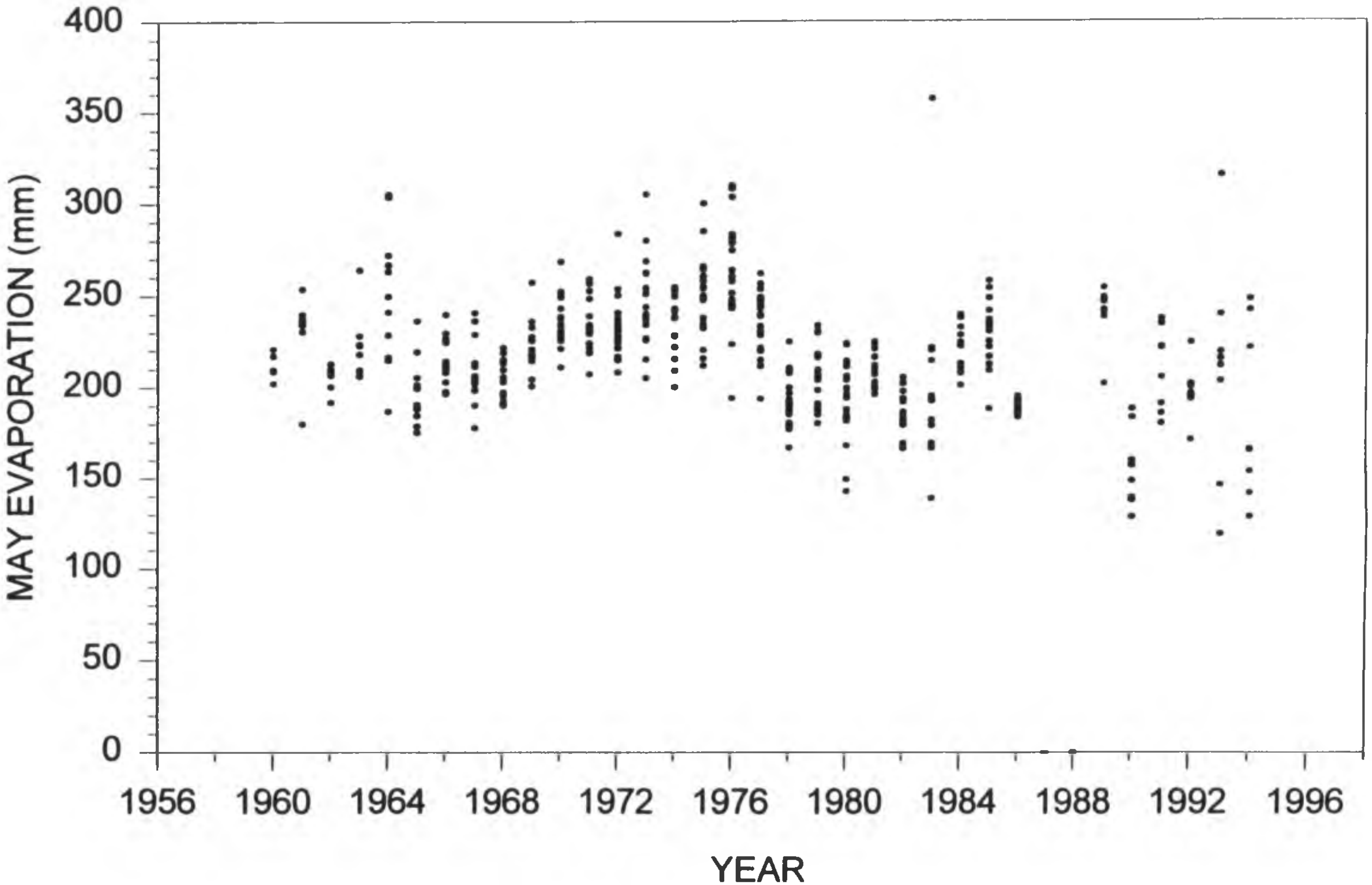


Figure 74. May evaporation by year for all stations 1960-1994.

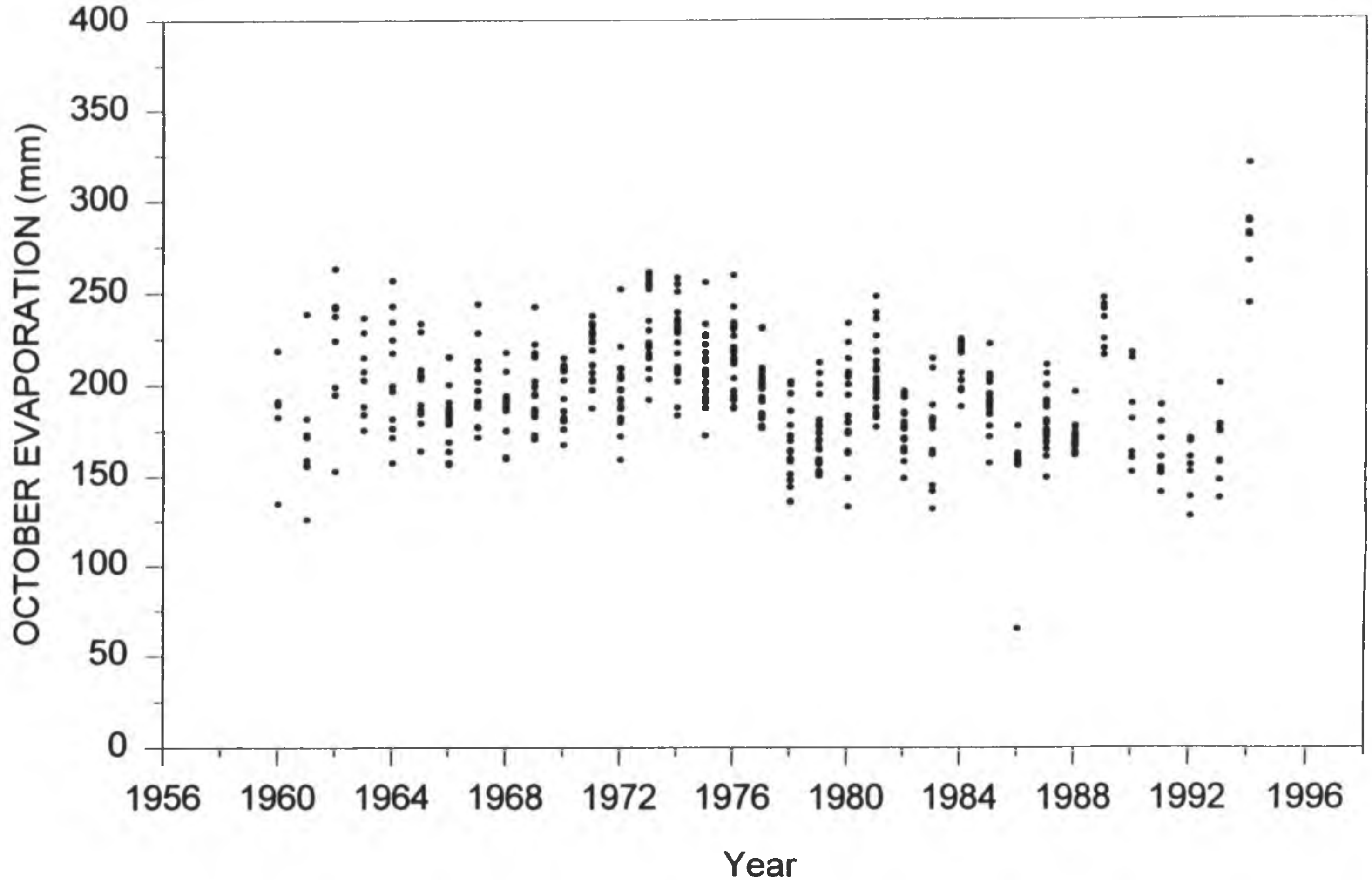


Figure 75. October evaporation by year for all stations 1960-1994.

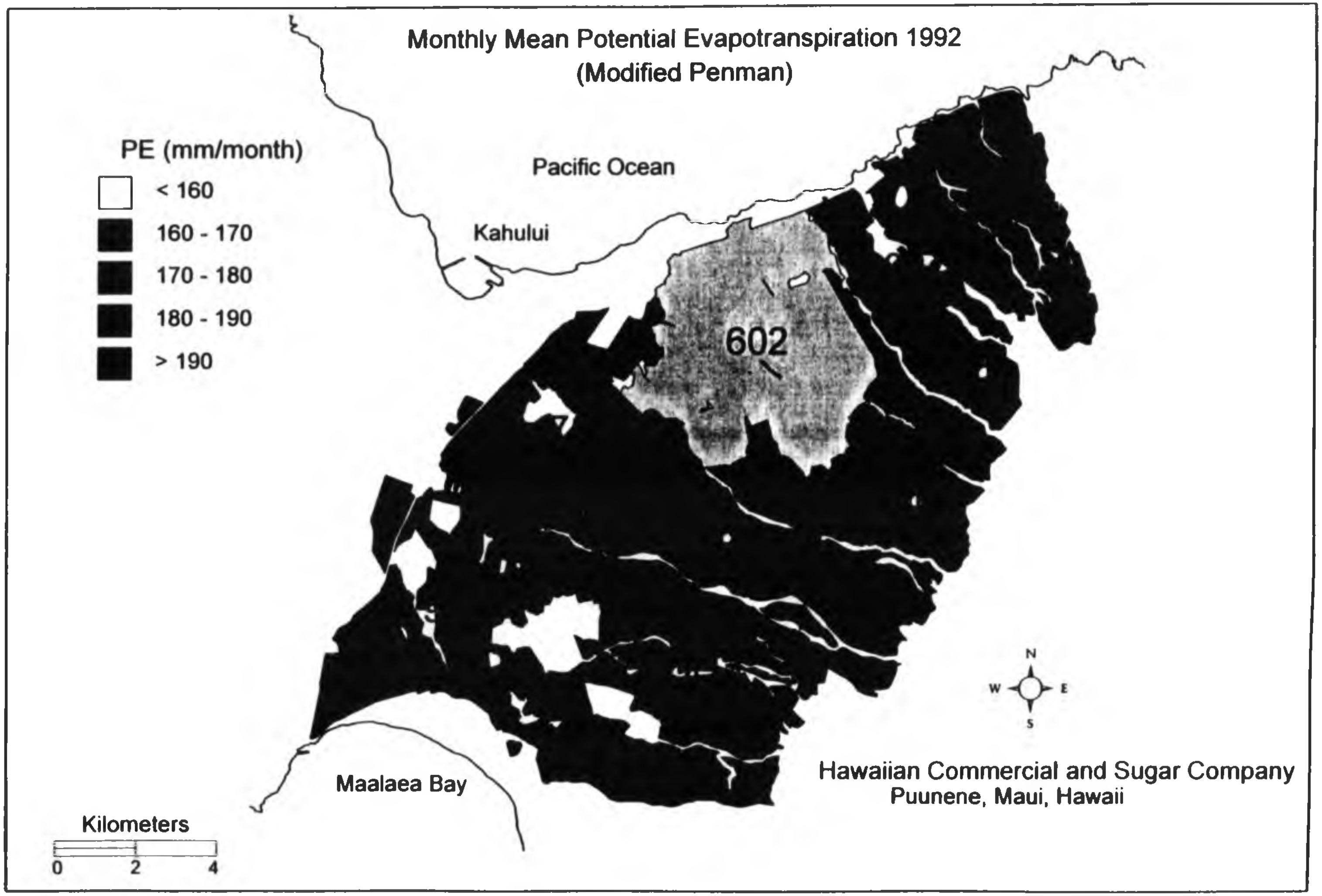


Figure 76. Map of mean monthly estimated evaporation 1992.

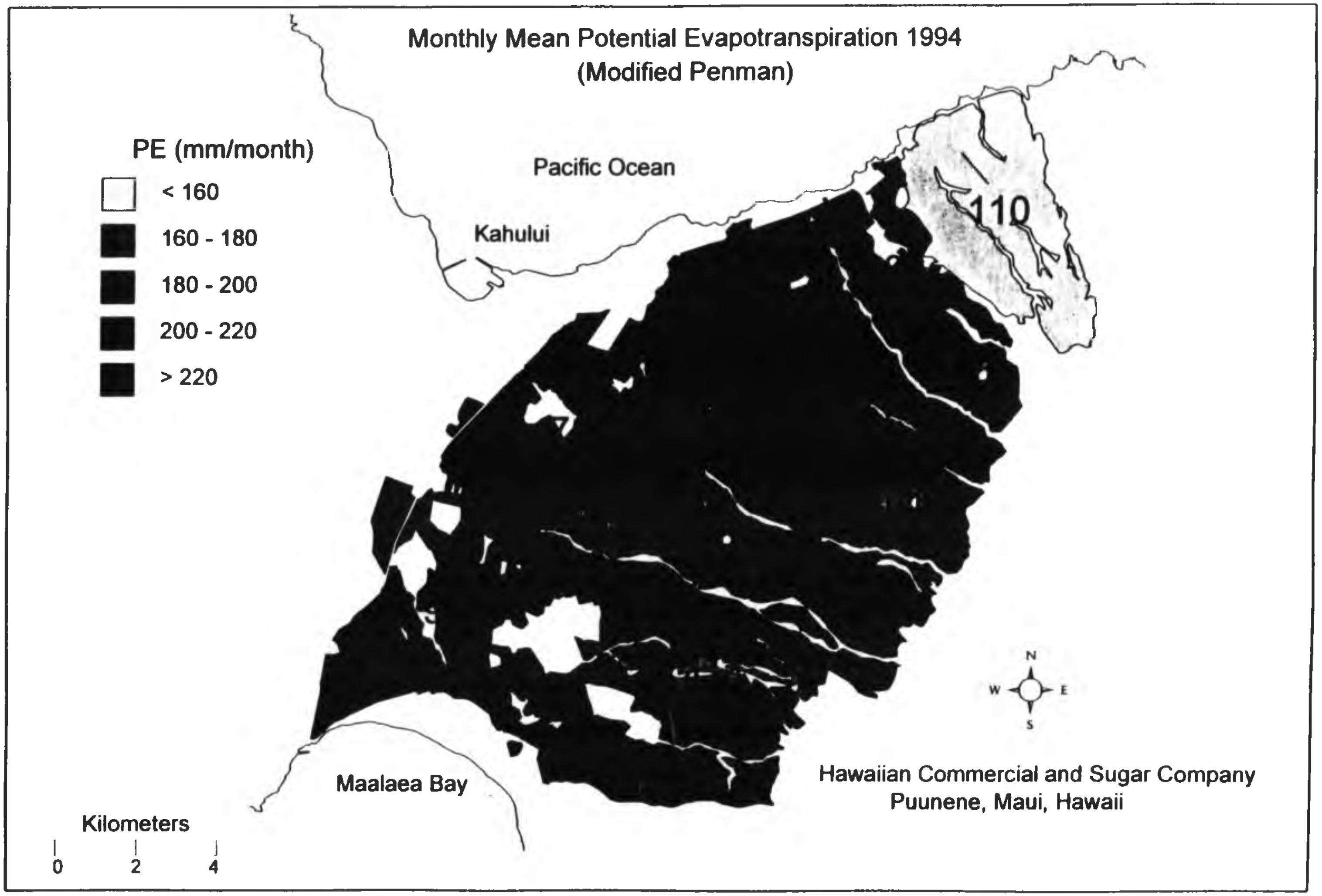


Figure 77. Map of mean monthly estimated evaporation 1994.

Penman equation to estimate advection. Advection may account for up to 30 % of evaporation. If PE is underestimated, calculations of adequacy and deficit will not be accurate. Evaporation (mm) by month for field 301 is notable in that October values are high (Fig. 79).

Figures 80-85 are graphs of evaporation (mm) by month for 1989-1994. Figure 80 can be compared to station 396 in the evaporation transect (Fig. 2 in Fig. 67) prepared by Nullet (1987). It similar in pattern to the Priestley-Taylor method of estimating evaporation. The spatial pattern of the mean monthly values presented in the maps Fig. 76 (1992) and Fig. 77 (1994) is reflected in the range of monthly values graphed in Fig. 83 (1992) and Fig. 85 (1994).

The only way to evaluate the accuracy of the monthly PE values would be to examine the raw data from the weather stations. The monthly weather data for 1994 differs most from an expected season pattern for Maui (Fig. 86). Such a great range of values could affect water distribution with too much water going some places and too little elsewhere.

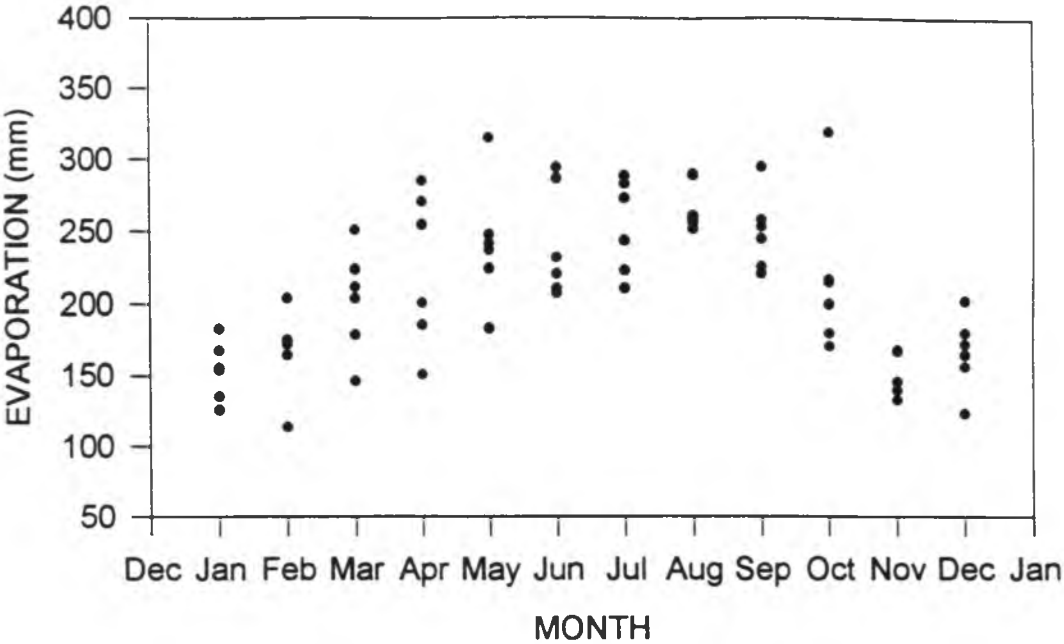


Figure 78. Mean monthly evaporation (mm) for field 906 estimated by the Penman method from automatic weather station data.

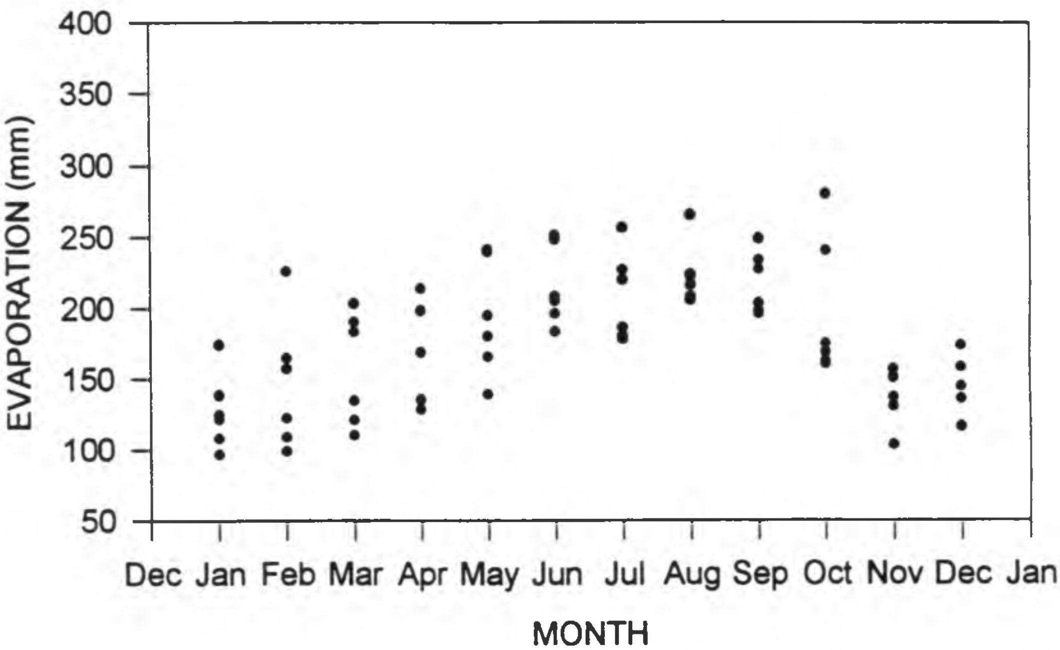


Figure 79. Mean monthly evaporation (mm) for field 301 estimated by the Penman method from automatic weather station data.

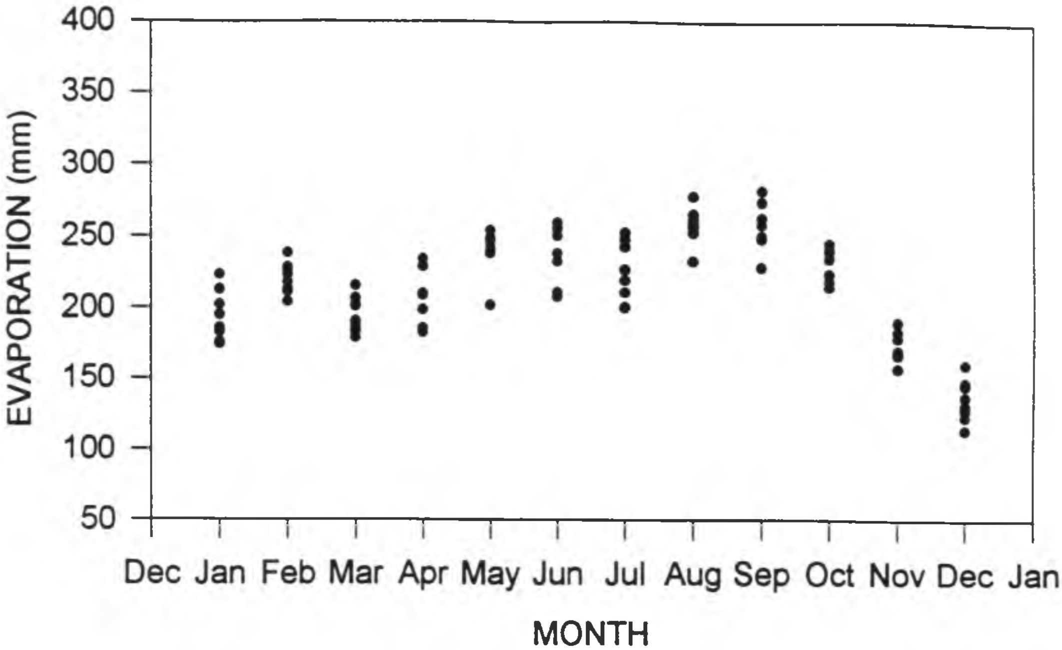


Figure 80. Mean monthly evaporation (mm) for 1989 estimated by the Penman method from automatic weather station data.

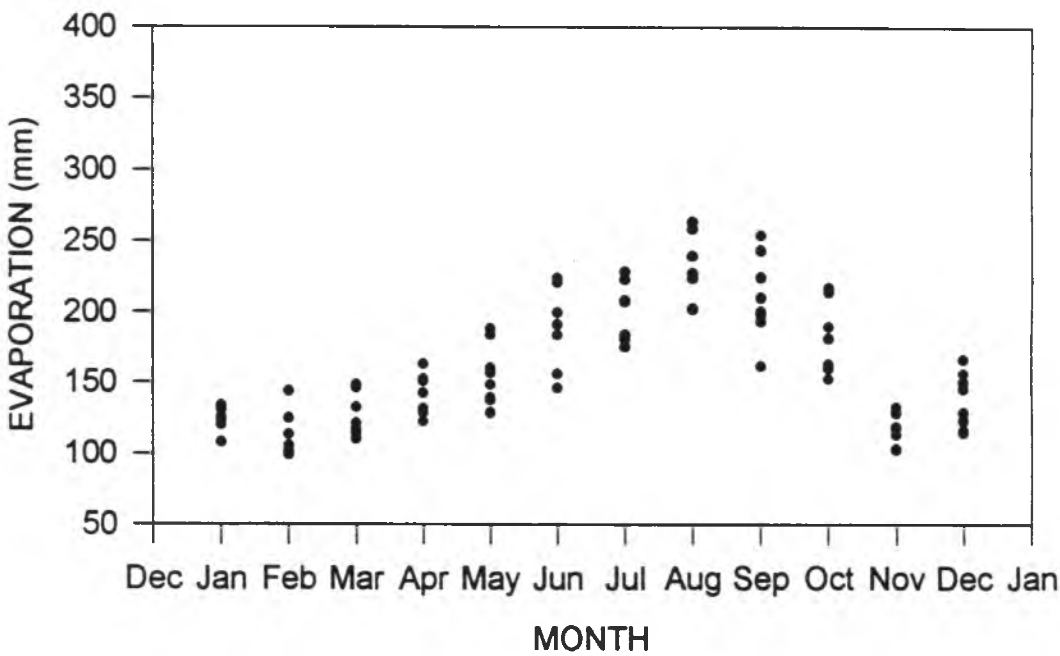


Figure 81. Mean monthly evaporation (mm) for 1990 estimated by the Penman method from automatic weather station data.

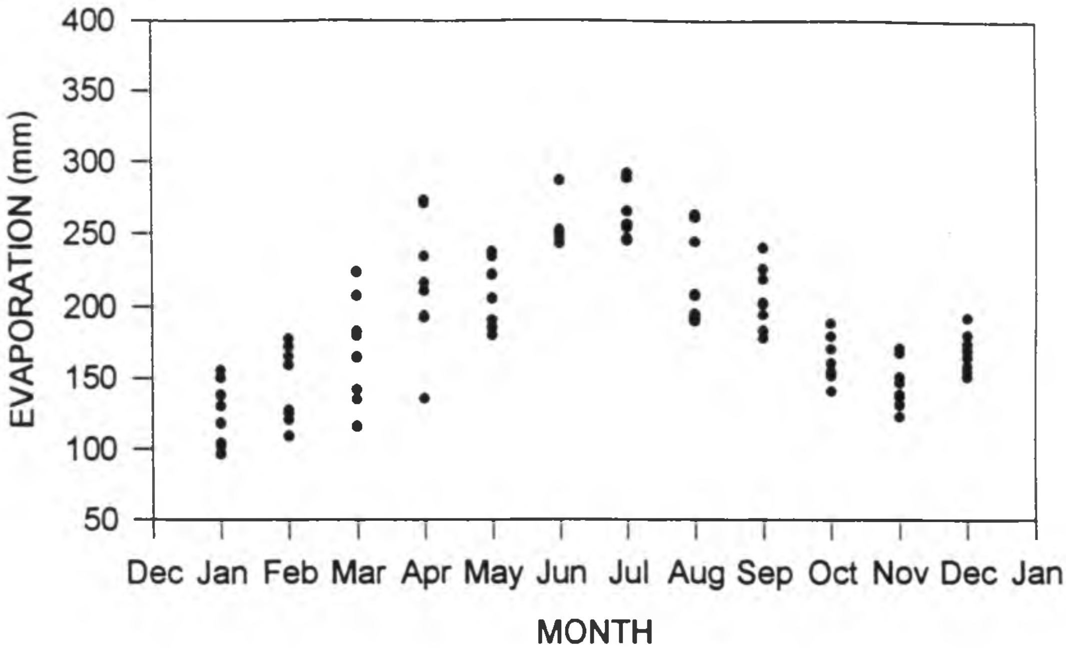


Figure 82. Mean monthly evaporation (mm) for 1991 estimated by the Penman method from automatic weather station data.

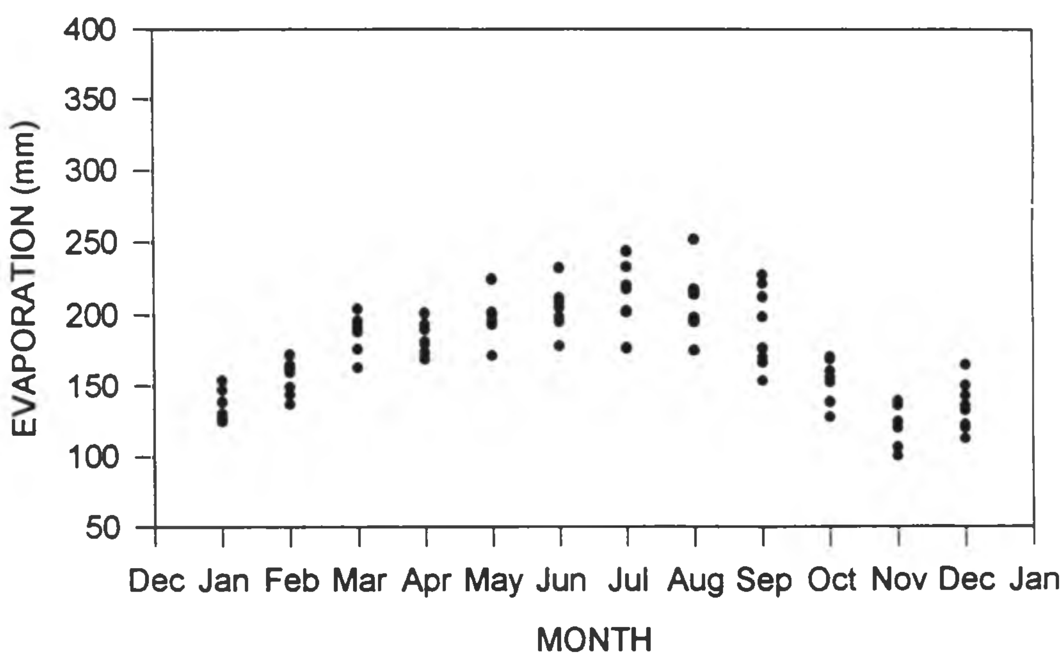


Figure 83. Mean monthly evaporation (mm) for 1992 estimated by the Penman method from automatic weather station data.

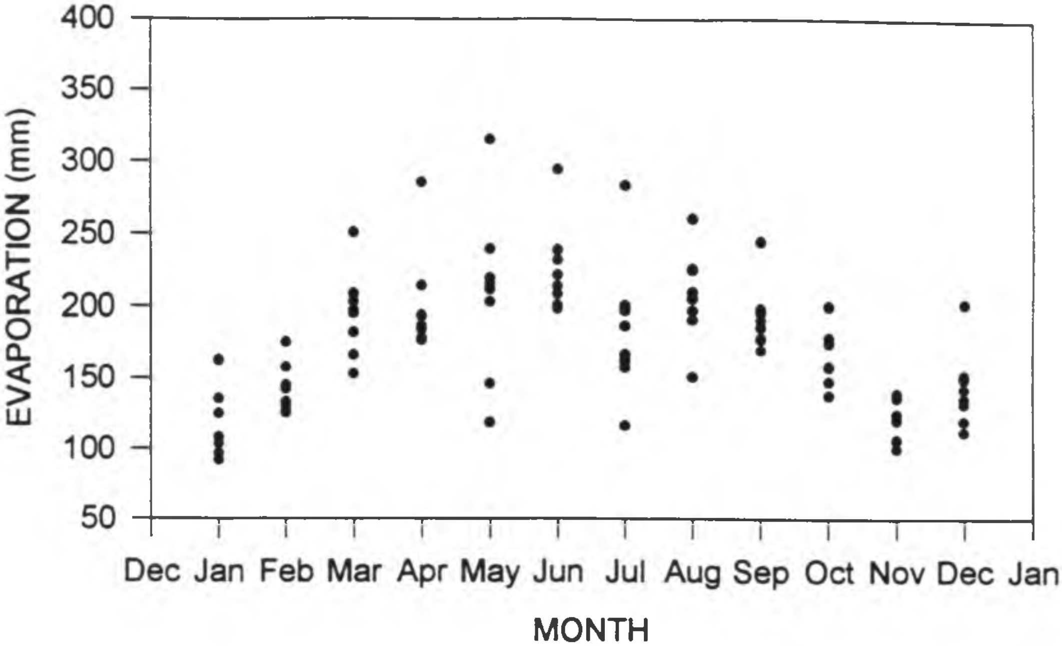


Figure 84. Mean monthly evaporation (mm) for 1993 estimated by the Penman method from automatic weather station data.

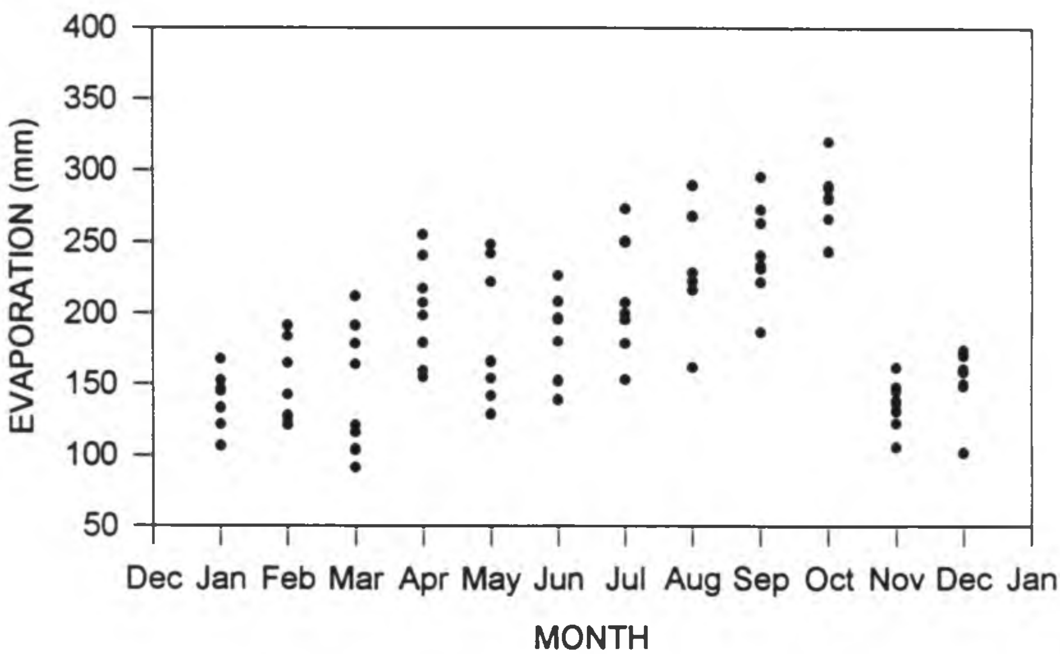


Figure 85. Mean monthly evaporation (mm) for 1994 estimated by the Penman method from automatic weather station data.

CHAPTER FOUR

DISCUSSION

Introduction

The emphasis on this study is on spatial information management. The maps, tables, and figures presented in the previous chapter are intended primarily for visualization of patterns in the data both in space and in time. The purpose is to try to understand the relative importance of the many environmental, technological, and management factors affecting sugarcane yield by examining change, similarity, and difference. This chapter covers some of the implications of the results.

Multivariate Analysis

With large datasets having many variables it is useful to use data reduction techniques to pinpoint where more analysis effort will be most worthwhile. An example of canonical variate analysis in Chapter Two illustrated that variables in the field history database contained spatial information consistent with the plantation map. Examination of the correlations on the canonical variates axis indicated that elevation was the variable most responsible for the differences. Additional examples of multivariate analysis presented in Chapter Three suggest that these methods are useful in spatial analysis and in separating out effects of different variables.

Using maps together with canonical variates analysis to identify areas of dissimilarity as well as similarity was found to be much more useful than maps alone. In looking for clues, both spatial and temporal, about the relationship between sugarcane yields, the biophysical environment, and management practices, variability must be looked at from different view. Identifying groups within which yields have responded similarly will help identify the nature of common factors.

Technological Change

Technological change at the plantation has had differing impacts. The conversion to drip irrigation resulted in higher yields for all fields converted. The mill waste yield, not converted to drip, had lower yield increasing the difference between low and high yields. The second technological change occurred when the network of evaporation pans was discontinued and replaced with a network of automatic stations designed to protect residential areas from cane smoke.

When a computer model such as the HC&S water balance model is used for irrigation management, the data represents the field conditions. With the conversion to drip irrigation, the cane was irrigated more often with smaller amounts of water. Increased precision in the evaporation estimates is needed to meet the water demand of the sugarcane with drip irrigation. This was a factor in the decision to convert to automatic stations.

Where to Put Water When Water is Short?

The best yields with drip irrigation are where the highest PE is. PE is not simply a spatial weather phenomenon. Different age and planting (harvesting) months have differing yield potentials. Cumulative effects of PE on cane production should be considered in optimizing where to put water. There is a strong seasonal component to solar radiation in Hawaii. Cane planted in August. September, October is getting established when days are shorter and solar radiation is reduced. Oldeman (1971) reported differences in yield by month of planting. He gives cooler temperatures and more rain when cane is getting established as factors in the lower yield with September, October, and November planting. Conditions for harvest also may not be as favorable. Clements (1980) shows that the best ripening time for cane is from February - June when temperatures are cooler. Cane planted at this time will have more sunshine to promote growth if other factors are not limiting.

With a network of weather stations, the differences between evaporation values may not seem that different between stations. Nonetheless it is the variation between stations that gives spatial information to the water balance. In drought years, the difference between stations is less. When there are strong trade winds and heavy windward rainfall, the gradient is steep between the more leeward and the windward stations. When other wind patterns or low pressure systems replace the trade winds, the between station variation will change.

Monthly potential evapotranspiration values calculated with data from the automatic station do not correspond with the expected spatial and seasonal evaporation patterns for the HC&S area of Maui. Located in the shadow of Haleakala, most of HC&S is arid. Abundant sunshine is excellent for cane production if water is not limiting. With little rainfall in the summer, the plantation is 100% irrigated. The potential evaporation estimates including advection should be twice those in winter with a strong seasonal pattern (Figs. 65-66). The sun is directly overhead in May and July with the longest days in late June and July. Weather in Hawaii is highly variable spatially, with sunshine and dryness increasing from windward to leeward and temperature decreasing with elevation. From the late 1980s until 1994 (the last year of data analyzed), it appears that advection may not be accounted for and some stations may be drifting but it is not possible to know for sure without examining the daily data.

In an experimental field with well-watered sugarcane, an automatic weather station with all sensors properly calibrated and functioning would have an advantage over an evaporation pan in that it is sensitive to smaller time steps of variation and can be used for real-time management. With sugarcane not limited by water and with quality information from weather stations, there should be no problems using a modification of the Penman equation (Doorenbos and Pruitt, 1977; Chang, 1961). However, HC&S in the summer (or during drought periods), when water is short and conditions are dry, advection can increase plant water demand to much higher levels than predicted by solar radiation alone. Under these conditions, pan evaporation values show a distinct summer peak. The lack of seasonal response to summer climate conditions in the HC&S monthly evaporation data has persisted since the late 1980s and the number of stations within the plantation is reduced. These problems warrant further investigation as a possible cause of reduced water use efficiency with drip irrigation.

Gibson (1978) recommended when the conversion to drip irrigation first took place that PE be used instead of soil moisture storage. HC&S chose to continue using the same soil moisture storage values they had with furrow irrigation. If PE estimates are accurate, the amount of water applied should replace what was used by the sugarcane. Under these conditions, SMS should be equal to PE (Gibson, 1978). The SMS values are much greater than daily PE values. If water is limited, less water is required to replace the daily water demand than it is to refill the soil moisture storage. Moreover, with drip irrigation, water is applied so slowly that refilling the total soil moisture storage will require the irrigation system to run much longer.

Most of the fields are high-yielding, conditions permitting. The field means are not significantly different at the fields level except for mill fields. The variation between years is much greater. To optimize where to put water according to location (soils) alone would not be making allowance for the great differences in yield by plant-harvest month or age. Moreover, using PE strictly as a daily location value does not allow for cane production in different fields at any time. Accumulated PE values by field may serve as an indication of the amount of solar radiation the crop has experienced.

Geographical Information Systems

Geographical information systems (GIS) are tools for displaying and manipulating spatial data. Developing them can be costly and time consuming. The previous chapter gives examples of using maps for spatial data visualization and graphs for viewing changes over time in the data as a preliminary to developing a GIS. Before investing in a GIS system, the question should be asked is will the output be useful and how much information does mapping alone provide.

Climate, soils, and vegetation spatial patterns cannot be considered independent as climate affects both soils and vegetation. Because a pattern is visible on a map does not mean the differences between elements of the pattern are statistically different. The effect may be created by the choice of legend categories not the spatial information in the data. Similar patterns on maps may indicate correlation, not cause and effect.

Using maps alone does not seem to be a satisfactory way of evaluating yield and water relationships at the plantation. The staggered planting dates make the plantation a mixture of many different sugarcane populations. The field history data is interesting in that the data is keyed on harvests and reflects the influence of planting time and age. The spatial patterns of the yields reflect the many factors involved.

Legend categories can be chosen arbitrarily and do not necessary reflect statistically significant differences. A combination of statistics and maps is a more powerful tool for analyzing spatial data. If there are not significant differences between variables representing different areas of the map, the variable should belong to the same category.

CHAPTER FIVE

CONCLUSIONS

A sugarcane plantation is a community of many populations of cane of different ages growing in diverse environments. As with changes in ecological systems, changes in the physical environment or at the management level can affect many factors of sugarcane production. It is not easy to evaluate the effects of perturbations in a system as some may not appear until years later. Analysis at the watershed, ecosytem, or plantation level involves evaluating variability over space and time.

Maps and multivariate analysis techniques can be utilized as tools to simultaneously view variables over space and through time. Scientific research has traditionally been experimental, covering little space and very short time periods. A concern among scientists today is how to apply these highly detailed studies to the global ecosystem scale. Different properties of ecological systems as well as patterns of variability can appear at different scales. Some processes of ecological systems can be detected only at large spatial and long temporal scales (Michener et al., 1994).

The change in irrigation technology to a more efficient drip system at HC&S plantation in the late 1970s and early 1980s not only increased yields but also changed the spatial pattern of yield. With furrow irrigation low elevation fields with high evaporative demand and coarser soils had lower yields than the higher elevation soils with high soil moisture storage.

With drip irrigation. water is applied in less quantity but more often than with furrow. The long interval between rounds with furrow irrigation meant a reliance on the soil's ability to store water. Analysis of yield data for the past 45 years suggests that yields from areas of the plantation with different soils are more uniform with drip irrigation than with furrow irrigation, and potential evapotranspiration becomes relatively more important as soil texture is less limiting. The most important structure of the plantation is the physical landscape including weather and soil variability. Dynamic processes at the plantation scale also revolve around the ever changing cycle of planting and harvesting. Potential evapotranspiration is not only a spatial variable, it is a physiological variable affecting sugarcane growth. Spatial yield variability is influenced by age and planting. Age and planting date are indicators of how much cumulative effect sunshine has on the sugarcane.

HC&S plantation has experienced droughts and shortages of surface water supply on and off throughout the years. The long record of excellence in sugar production at HC&S is evidence that management has been flexible enough to maintain sugar yields in the face of environmental fluctuation. Weather at HC&S is not only highly variable both spatially and temporally, it is unique to Maui. The best management guide for HC&S is their own plantation's history.

The acreage of the plantation has increased to 14,500 hectares with more than 150 fields. The results of this research show that the increased water efficiency of drip irrigation with more frequent, smaller applications of water made differences in soils less important. Sandy soils that were relatively unproductive under furrow irrigation became highly productive under drip irrigation. With smaller amounts of water applied more often, more precision is needed in estimating evaporation.

The best yields with drip irrigation were in the 1980s with exceptional yields in all areas of the plantation in 1987. The ever-changing schedule of planting and harvest makes it nearly impossible to reproduce the conditions of an exceptional year. Changes already in motion in 1987 would begin to reduce the benefits of drip conversion. The age at harvest for the sugarcane was getting younger and younger. Environment concerns over cane smoke switched emphasis of weather stations to wind-monitoring rather that the traditional emphasis on pan evaporation. Many other possible factors may be involved in the change including the age of the drip system, changes in the scale of management, increased reliance on computers, and fewer employees in the field.

If other factors are not limiting, solar radiation relates directly to cane production (How, 1986). With drip irrigation, low soil moisture storage is less limiting than it was with furrow, thereby reducing some of the variation due to soil differences. During the summer, HC&S relies about 100% on irrigation. If water supplies are low, water is pumped from wells to supplement the surface irrigation water supplies. With well-irrigated cane, potential evapotranspiration closely corresponds with solar radiation. In Hawaii, the sun is directly overhead in May and again in July making solar radiation values for dry areas much higher in summer than winter. Under dry conditions, the sun heats the ground. Advected heat, moved by the northeast trade winds over the island, will increase water stress on sugarcane plants downwind. In leeward areas and along the central area of Maui where the plantation is located, potential evapotranspiration in the summer can be double that in winter.

Pan evaporation was developed as a method to estimate how much water is needed by the crop. A sugarcane crop on a sunny day with a full canopy and unlimited by water will transpire water at a rate approximately equal to open water evaporation (Chang, 1968). Evaporation from a pan is an integration of environmental effects such as humidity, solar radiation, wind, and temperature. The high spatial variability of weather in Hawaii reflects the influence of the mountains blocking the trade winds. Weather varies not only from leeward to windward but also with elevation.

Good weather only makes good yields if no other factors are limiting. Much of HC&S has such low yearly rainfall it can be classified as desert. The high solar radiation combined with sufficient irrigation result in a high sugarcane yield potential. Windward sugarcane plantations had plently of water but did not have enough sun to produce cane. However, the price of all the sunshine is the need the manage water very well. Numerous high yields in the field history database indicate that the plantation has been managing the spatial and temporal variability of water demand very well.

When sugarcane is stressed by heat or lack of water, yields reflect how well management was able to help the sugarcane meet the stress. The pan evporation stations were located in the sugarcane fields in a network designed to collect data that best represented crop water demand. Advection increases as wind moves over land; stations were located downwind of one another through the plantation. Although furrow irrigation is less efficient than drip irrigation, yields under furrow were very good, and variability was low. The first ten years of drip irrigation, still using pan evaporation, were very successful.

With the change to automatic stations, the scale of information collected on water demand was reduced to almost half. One station represents at least 20 fields. Evaporation pans represented the same areas but with more stations. If data are missing, a large area of the plantation is not represented. If the data used in the modified Penman equation is not spatially accurate, the modified Penman estimates will not be representative of field conditions. Any loss of information on field conditions will hinder management's abilility to meet the water demand of the sugarcane. The reduction in data quality for potential evapotranspiration reduces the quality of irrigation scheduling.

The current weather station network is designed for wind monitoring during cane-burning as a response to community concerns. The pan network was discontinued as the new automatic stations were added. Only two of the stations are located in fields where evaporation pans were located. Weather data must be recorded together with the collection location. It is possible to interpolate, generate, or extrapolate weather data, but borrowing of data from another location when the weather station is not working is a loss of information and can increase inaccuracy. With more stations, values can be interpolated to provide estimates for the missing data or historical data can be used to generate weather data for the site.

Recommended areas for checking the potential evaporation values calculated with data from the automatic weather stations:

1. Evaluate the spatial variability of pan evaporation data. The automatic stations should be centrally located in the area of extrapolation. Assigning the modified Penman values to where the evaporation pans used to be does not make sense spatially.

2. Check the location and accuracy of all input data used in the modified Penman estimates. If sensors are drifting, not calibrated properly, or data borrowed from elsewhere, it could affect the PE estimates.

3. How well does modified Penman estimate advection? Advection could cause the calculated PE to be up to 30% lower than actual sugarcane water demand (Ekern, personal comm.). In the daily water balance this would mean 100% adequacy might actually be 70%. If potential evapotranspiration estimates are low, the cane will not be receiving enough water. Doorenbos and Pruit (1977) caution that in areas with more daytime wind than nighttime, Penman estimates can be 15 - 30% low.

4. Before changing the water balance or water distribution which worked so well the first ten years with drip irrigation, examine the quality of all input data, including the pan assignments and key station assignments. If data quality is confirmed, the data should be changing as conditions on the plantation change. The water balance model itself should remain constant. If something is wrong with the data, it may appear that the model is not working properly.

The scale of management should be determined by the scale of the data. If the plantation were to manage water at the irrigation block level, there would be over 1000 management units. If one field is planted at one time with one variety, the field is the management unit. If only 9 PE values are entered into to water balance, water is actually managed at the pan group level of information, not the irrigation block level. Similarly, if a fertilizer such as potassium is applied at only 3 levels, the scale of fertilizer application is much more general than the soils sampled. Management can only respond to environmental variability if they have representative data. If the data are not representative spatially and temporally, then misinformation will prevent good water management.

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